Development of Room-Temperature Radiation Detectors based on CdZnTe and CdMnTe Crystals

Stephen Babalola

Collaborators

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OEP - VFP Noel Blackburn et.al.

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U. Roy

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L. Li

DOE-NNSA MSIPP University Members
Fisk Univ. - A. Burger; ASU - J. Billa; MOREHOUSE COLLEGE - J. Hall, J. Brown;
SUNO - M. Elaasar, J. Omojola; PVAMU - J. Fuller; SUBR - E. Walker

Outline

- UL-CORDA
- Introduction -Radiation Detectors
- Research
- MRL

DOE-NNSA MSIPP

Universities-Laboratories Consortium for Radioisotope Detection and Analysis

(UL-CORDA)

$3,000,000.00 over 3 years

2012-2015

Sponsored by DOE NNSA Office of Workforce Development.

Program Manager

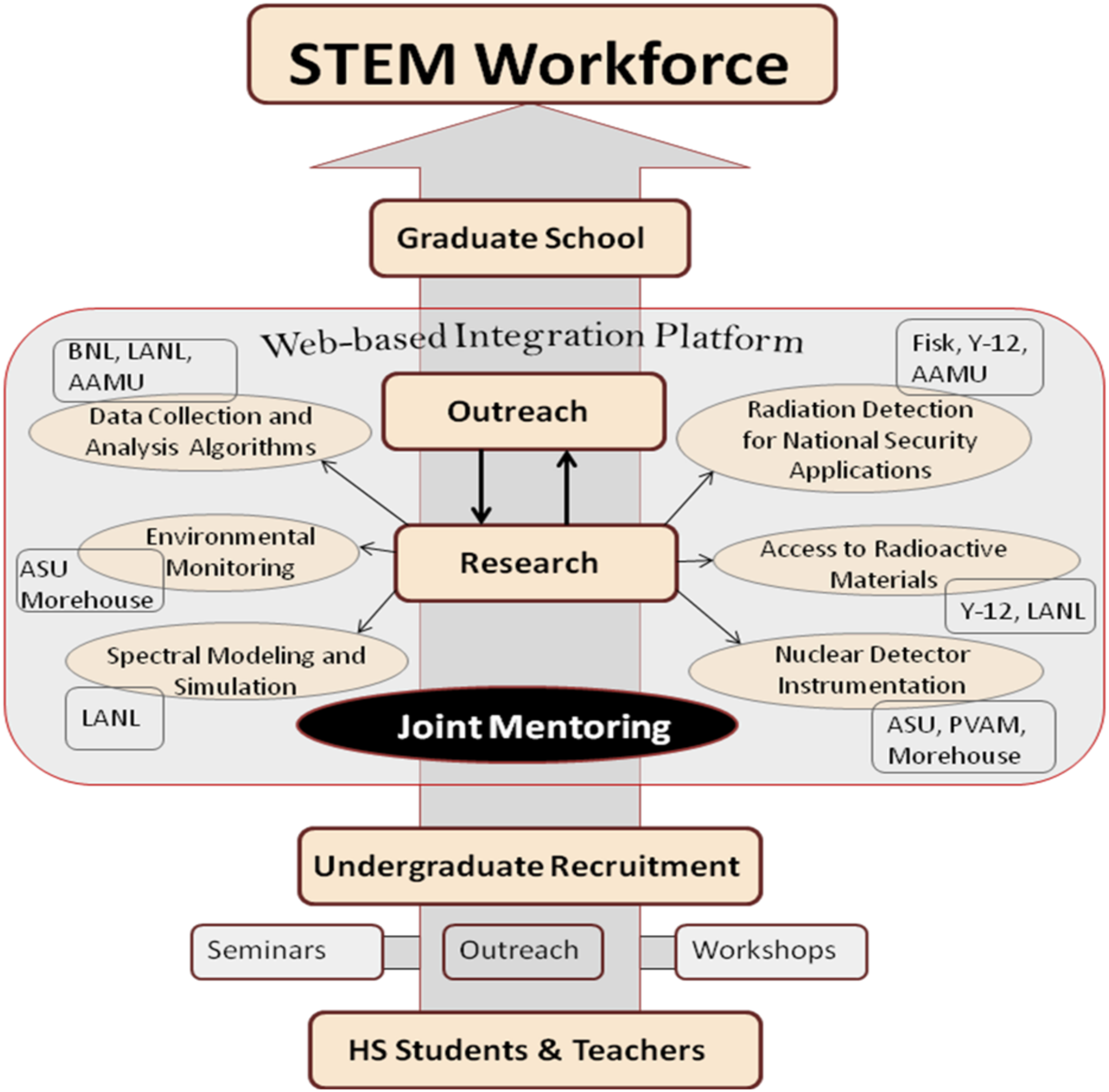
Jonathan Jackson.

PI and Consortium lead

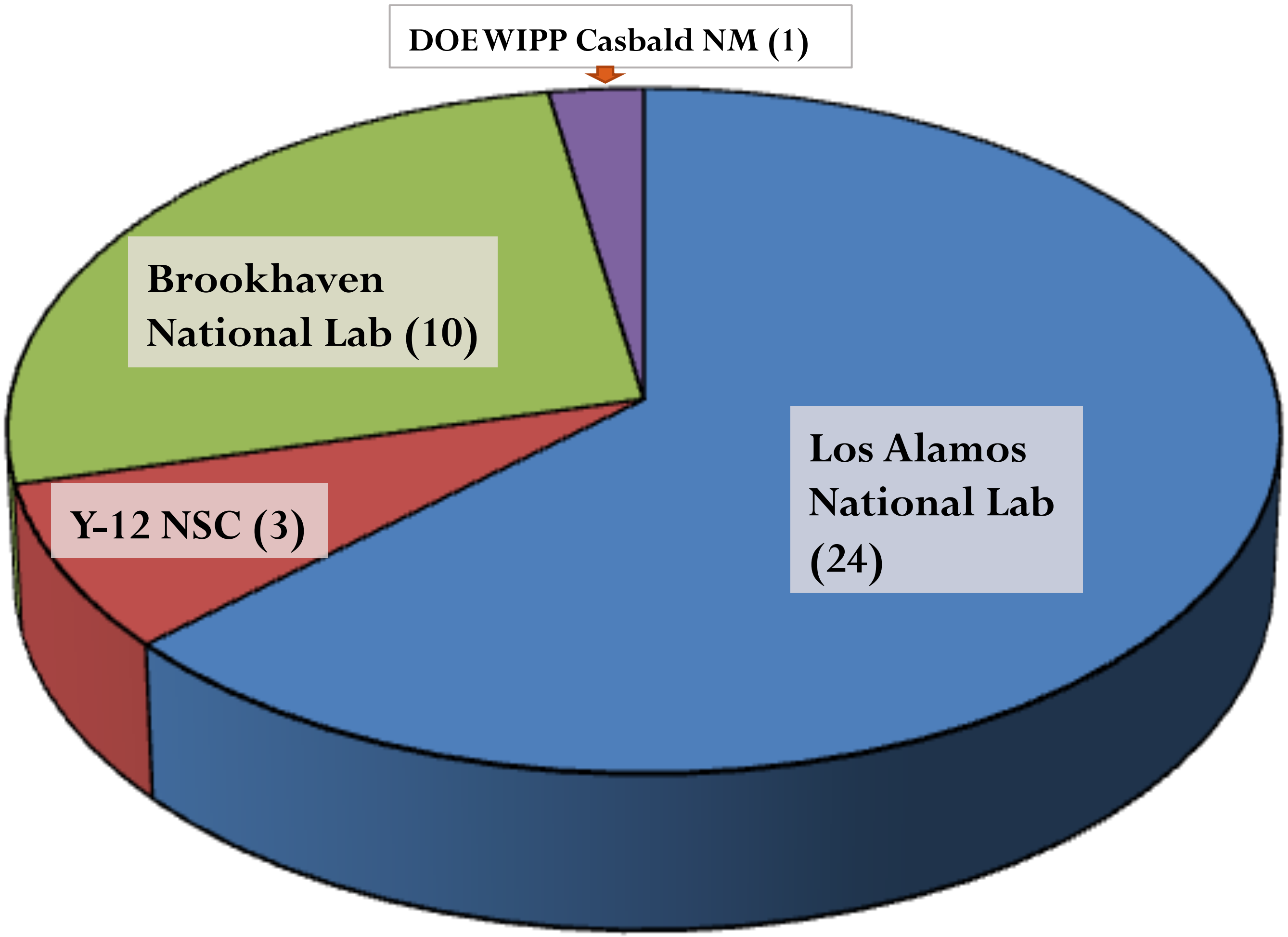
Dr. Stephen Babalola

Consortium Members

Dr. Cheslan Simpson
Dr. Ashley Stowe
Dr. Arnold Burger
Drs. John Fuller and Lijun Qian
Dr. Ernest Walker, Dwayne Jerro
Dr. Mostafa Elaasar
Drs. Jermiah Billa, Steve Adzanu
Drs. Trent Montgomery, Stephen Babalola
Drs. James Brown, Juana Mendenhall


STEM Workforce
Graduate School
Web-based Integration Platform
BNL, LANL, AAMU
Data Collection and Analysis Algorithms
Outreach
Fisk, Y-12, AAMU
Radiation Detection for National Security Applications
Environmental Monitoring
ASU Morehouse
Research
Access to Radioactive Materials
Y-12, LANL
Spectral Modeling and Simulation
LANL
Nuclear Detector Instrumentation
ASU, PVAM, Morehouse
Joint Mentoring
Undergraduate Recruitment
Seminars
Outreach
Workshops
HS Students & Teachers

UL CORDA Student Internships at National Laboratories



Progress and Success

DOE_NNSA MSIPP University-Laboratory Consortium for Radioisotope Detection and Analysis (UL-CORDA)

Achievements

- **Pipeline:** Over 250 direct participants of pipeline-development STEM activities (workshops, outreach, summer camps and internships at DOE national laboratories.
- **Internships:** 34 DOE laboratory interns and 70 interns at member universities , visited by national laboratory scientists for seminars and interaction.
- **Publications:** More than 10 published papers
- **Joint Mentorship and Education** between National Laboratories and member Universities. (e.g. Los Alamos national laboratory scientists taught MCNP course, and work using MCNP has been published).
- **Ph.D candidate:** One MSIPP-supported Ph.D candidate in the pipeline, conducted research at Los Alamos National Lab., and published papers.
- **Workshops:** Two MCNP workshops, one high school teacher workshop and 1 MCNP workshops led by lab scientists.

Success Stories

1. **(R&D 100 Award): Brandon Wiggins** with Drs. Burger (Fisk) and Stowe (Y-12), won a 2013 R&D award for their work on LiInSe2 thermal neutron detector.
2. **Jadtrl Heard**, ASU Health Physics Graduate Student – LANL Fellowship, Dr. Billa & Dr. Simpson joint thesis supervisors.
3. **Matthew Carradane**, ASU Health Physics Graduate Student, LANL Fellowship, Dr. Billa & Dr. Simpson joint thesis supervisors.
4. **Jonathan Lassiter,** AAMU Physics Graduate (PhD.) student, NASA Fellowship, Dr. Stephen Babalola and Dr. Jessica Gaskin (NASA) joint dissertation supervisors.
5. **Samuel Uba,** AAMU Physics Graduate Student, Dr. Babalola and Dr. Ralph James (BNL) joint thesis supervisors.
6. **Maxx Jackson,** AAMU Physics Graduate Student, Dr. Babalola and Dr. Stowe (Y-12 NSC) joint thesis supervisors.
7. **Innocent Tsorxe,** ASU student and Fisk Internship participant, secured job as Health Physicist in Dept. of Nuclear Engineering at Texas A&M, while pursuing his Masters degree.
8. **Alvin Jackson,** Secured a job at Entergy / Grand Gulf Nuclear Plant.
9. **Ashley White**, ASU graduate, secured a job at a biomedical device manufacturing company in Texas.
10. **Dr. Jermiah Billa** - Outstanding Mentor & Excellence in HP Program Development Award at Health Physics Society (HPS) meeting, Baltimore, MD, 2014.
11. **10 Publications in Journals and Proceedings and 43 Student Presentations at Scientific Conferences**

DOE-NNSA MSIPP UL - CORDA   DR. YONGGANG CUI   JULY 18, 2014

WORKSHOP

FPGA AND READOUT ELECTRONICS

Topics

Radiation Detectors and Output Signals

Signal Processing

Front-End Electronics

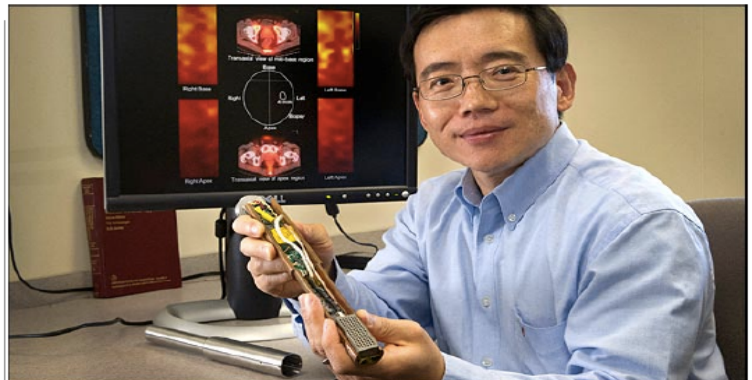
Digitization and FPGA

ADC + FPGA for Spectroscopic Applications

FPGA Readout for Photon Counting Applications

Workshop Info

Date: Friday July 18, 2014



Dr. Yonggang Cui

Dr. Yonggang Cui is a scientist at Brookhaven National Laboratory with over 15 year experience on nuclear radiation detection and application. He has extensive expertise in readout electronics for radiation detectors, design of radiation ... Cui has bu...

BNL scientist, Dr. Yonggang Cui, holding workshop on FPGA at Alabama A&M University

CdZnTe (Introduction)

CdZnTe is an excellent choice for compact, portable and rugged radiation detectors at room temperature

Attractive properties

- High atomic number (Z).
- High band gap (E_g) = 1.5 eV - 2.2 eV.
- High mobility-lifetime product ($\mu\tau$) of charge carriers.
- Size

=

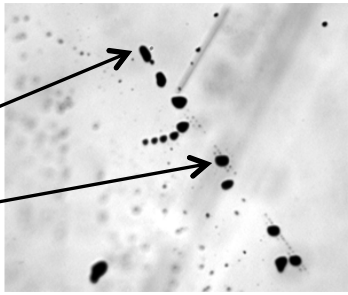
Good Resolution for radioisotope identification

Major Drawback of CZT Detectors

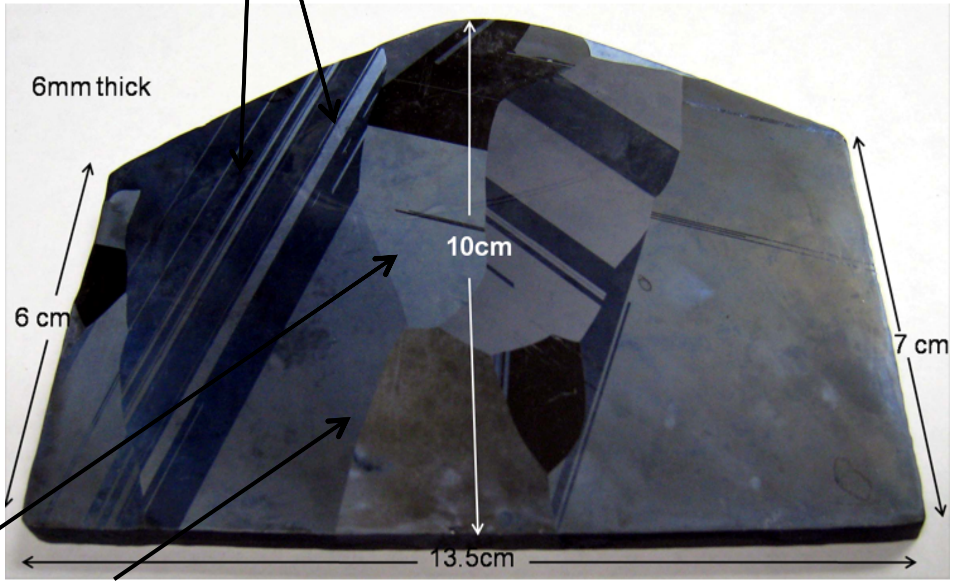
Sub-optimal quality of commercial bulk crystals due to **defects**

Material defects

- •Multiple crystals. (Grain and twin boundaries)
- •Te-rich inclusions and precipitates
- •Dislocations
- •Impurities (Deep/shallow levels)



Te inclusions



Twins

Grain boundaries

Fabrication-based limitations

- •Surface conditions
- •Surface roughness/scratches – Polishing
- •Chemical modifications – Etching, other processes
- •Oxide layer formation and interfaces
- •Reproducible manufacturing processes to produce high yields and acceptable costs.

Research

White beam X-ray diffraction topography (WBXDT) studies of Bridgman Grown CdZnTe crystals

S. Uba, S. Babalola, A. Hossain, R. James, "*Characterization of Extended Defects Observed in Cadmium Zinc Telluride (CZT) Crystal*", MRS Proceedings Vol. 1792 pp. mrss15-2134263, Cambridge University Press, 2015

Modeling of CZT response to Gamma photons using MCNP and Garfield

Influence of Thermal Treatment on the Monocrystalline CZT and Tellurium Inclusions

J. Lassiter, C. Payton, M. Jackson, S. Uba, C. Muntele, S. Babalola, "*The Influence of Thermal Treatment on Monocrystalline CZT and Tellurium Inclusions*"MRS Proceedings Vol. 1792 pp. mrss15-2136240, Cambridge University Press, 2015

White beam X-ray diffraction topography (WBXDT) studies of Bridgman Grown CdZnTe crystals

- VFP 2014 Research
- Presented as a contributed oral presentation at MRS Spring Meeting, San Francisco, CA. 2015
- Published as MRS Proceeding

S.Babalola, S. Uba, A. Hossain, G. Camarda, R. James, T. Montgomery, "*White beam X-ray Diffraction Topography (WBXDT) Studies of Bridgman Grown CdZnTe Crystals*" , MRS Proceedings Vol. 1792 pp. mrss15-2134972, Cambridge University Press, 2015

Batch Bulk Qualitative Analysis Challenges

Defects have been studied by

- Infrared Imaging (Transmission) – Te inclusions and precipitates
- Infrared Imaging (Reflection) – Etch pits and surface defects
- Electrical characterization
- Detector response

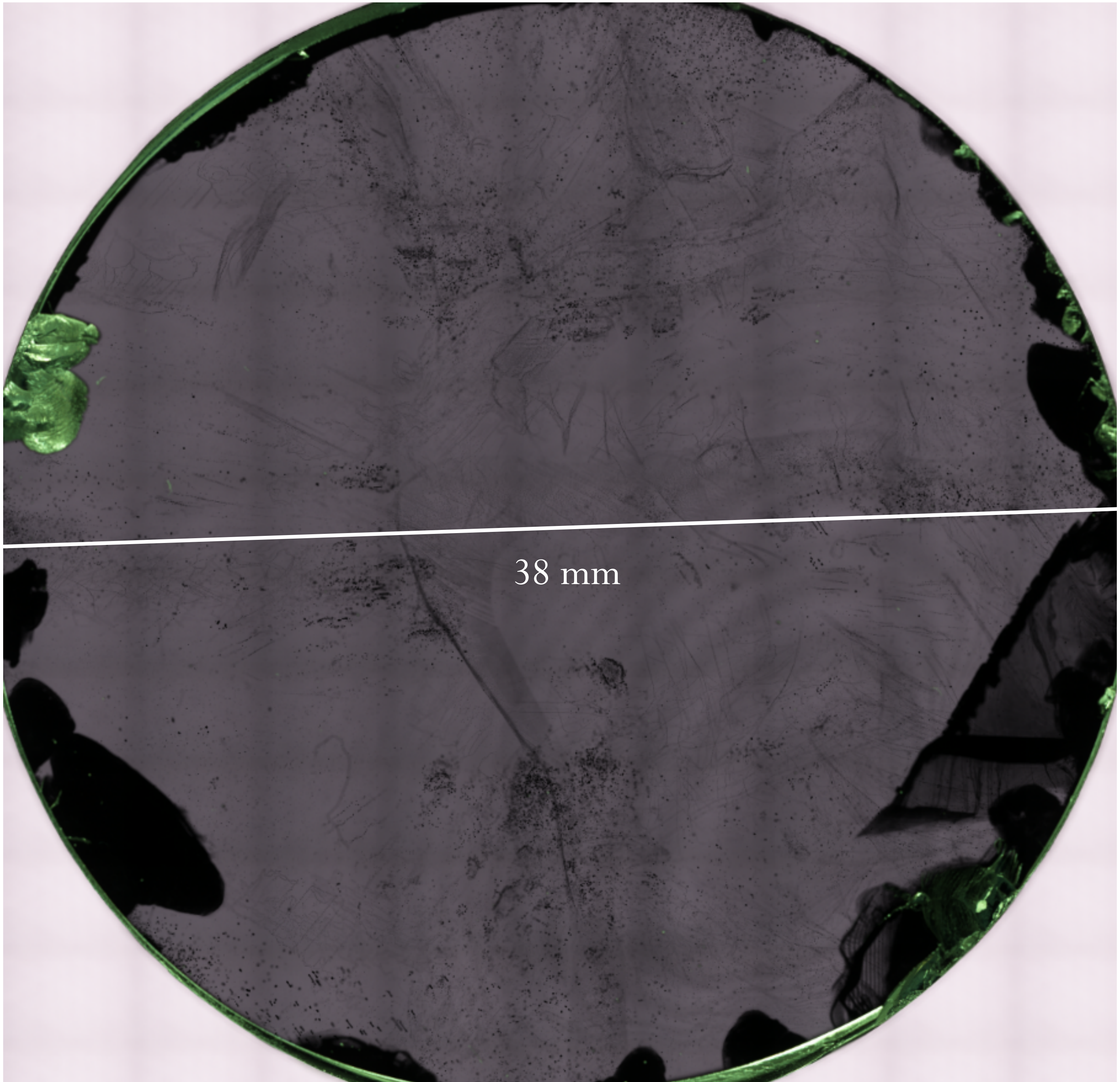
Drawbacks:

- Time-consuming detector fabrication processes
- Not suitable for large wafers
- Expensive for batch bulk crystal evaluations.

Challenge: Evaluation method for quick, accurate bulk and batch crystal evaluation to drive profitable commercial production of detector-grade CZT crystals.

<u>Solution: WXDT for batch crystal processing</u>

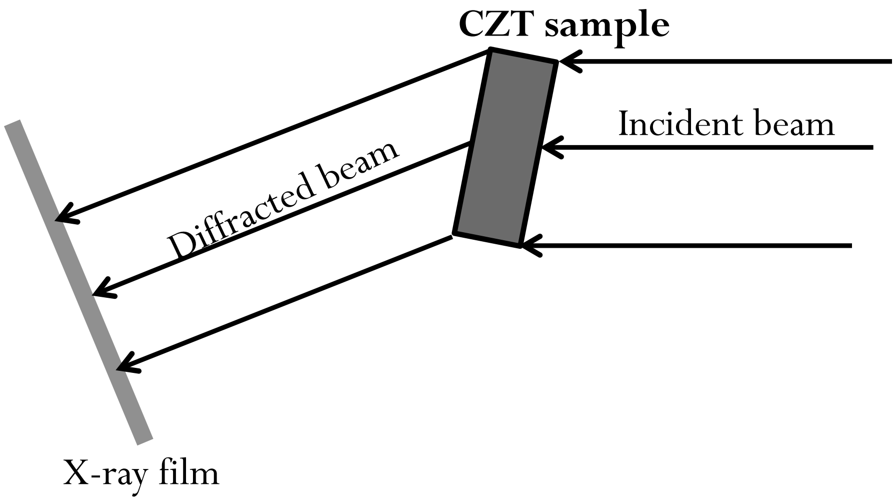
1) Employs synchrotron radiation.
2) Quick and ideal for batch processing, supports large scale production
3) Economically viable.

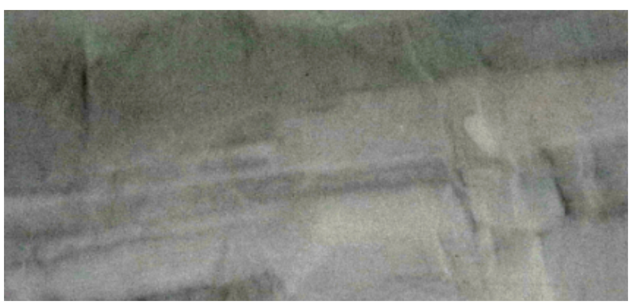


IR image (transmission) of CZT wafer

- Limited focal depth
- Does not reveal sub-grain boundaries
- Time-demanding

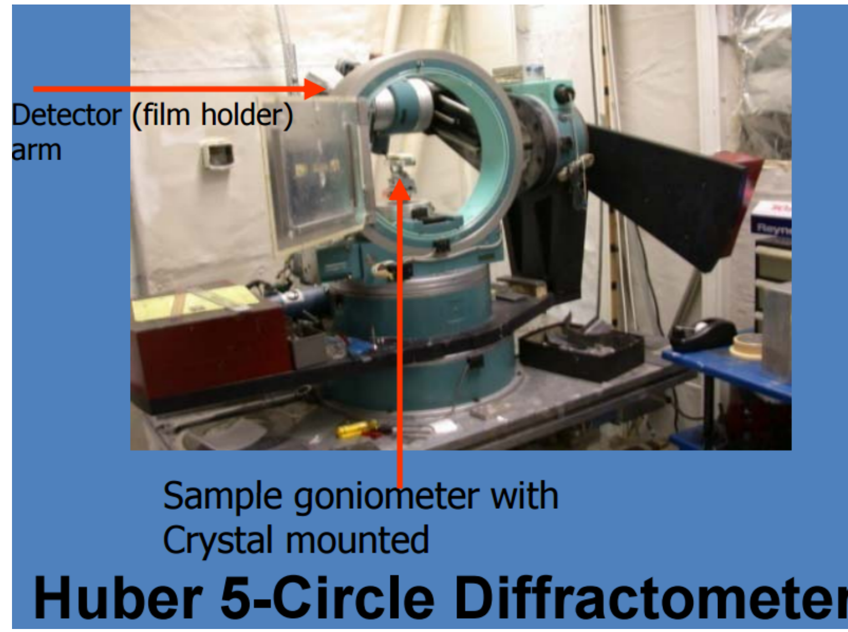
X-Ray Diffraction Topography (Transmission)





Diffraction pattern of several large area diffraction spots, each one of which is a high resolution X-ray topograph revealing irregularities in the crystal lattice

X-19C beamline: WXDT at DOE's National Synchrotron Light Source (NSLS), Brookhaven National Lab.



Huber 5-circle goniometer with computer-controlled robotic detector arm for positioning x-ray detectors

- Sun Ultra 5, Solaris 7 using SPEC software package (fourc) for motor control
- Scanning stage for scanning large-size crystals (up to 12" long)
- Slit-defined white radiation
- Darkroom for processing (developing, washing and drying) x-ray films

Experiment

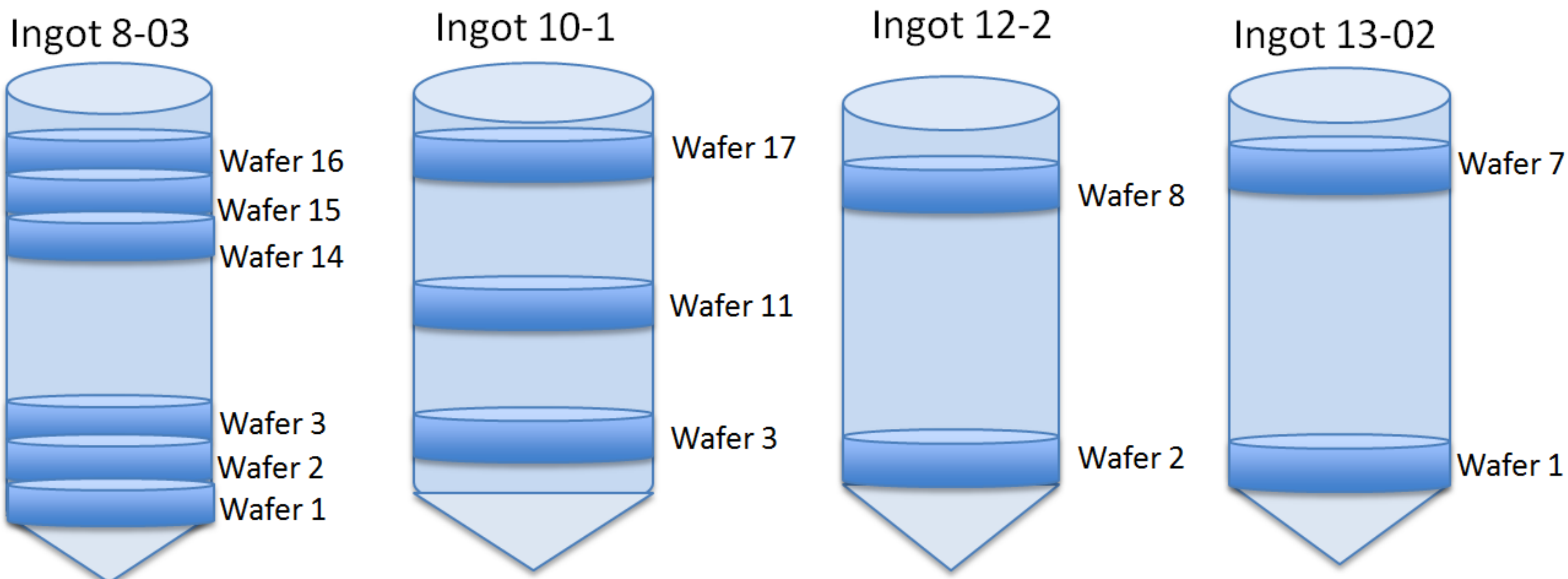
Sample Preparation

- Lapping and Polishing: SiC discs of decreasing roughness
- Final polishing with Al_2O_3 powder
- Organic cleaning with Methanol and de-ionized H_2O
- Etching with 5% bromine-methanol solution (in some cases)

White Beam Characteristics

- Large area beam of low divergence & high intensity (50 mm×5 mm)
- Small source (300 μm×100 μm) & large source specimen distance (25 m)
- Good spatial resolution capability (~ 0.04 μm) • Broad wavelength range (0.3 - 1.6 Å)

We selected 4 ingots as follows:



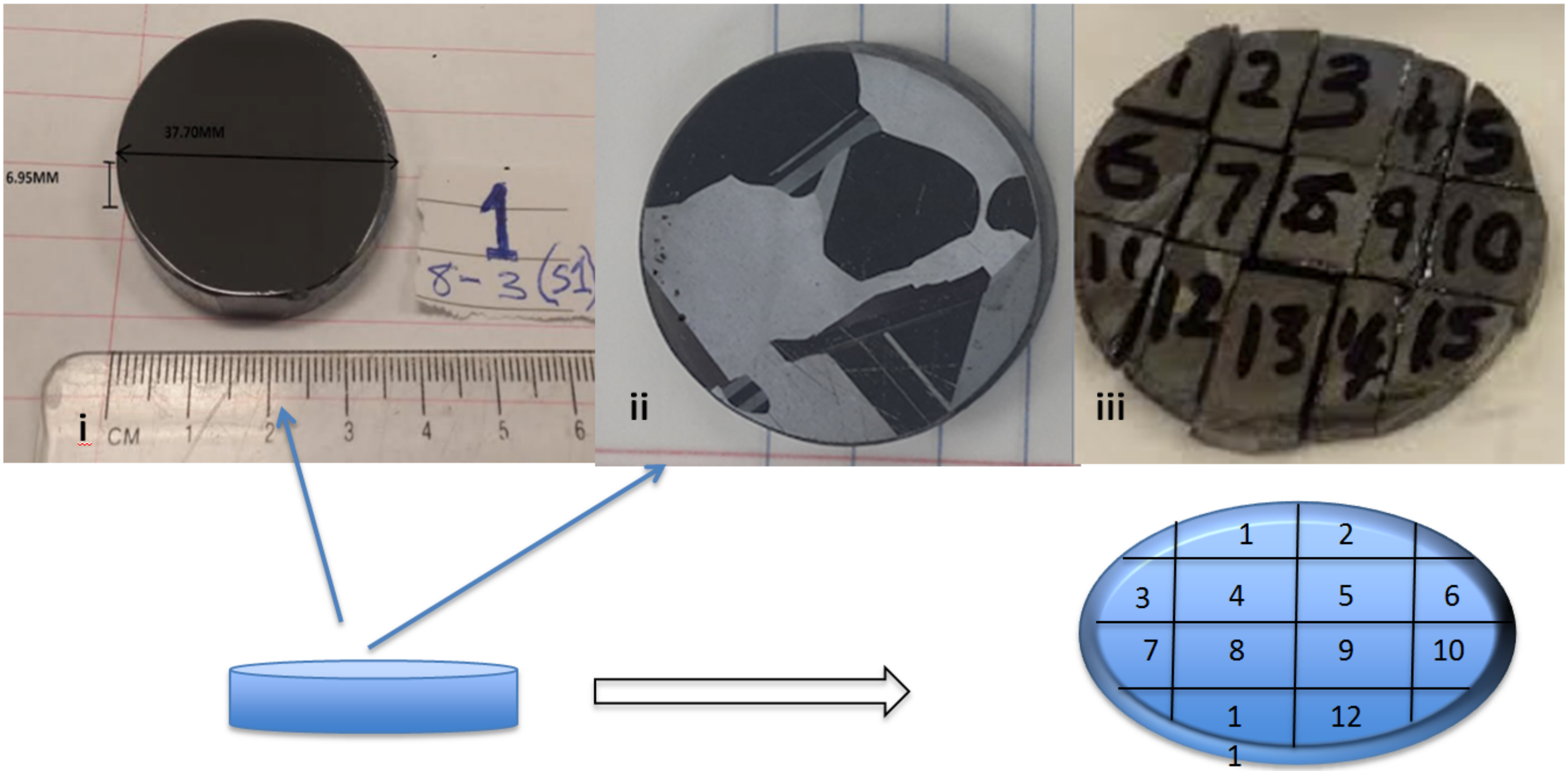
No choked seed

Choked seeding

Choked seeding

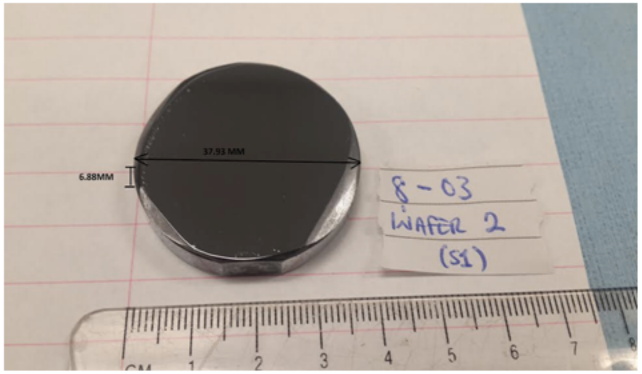
We polished the selected wafers, and looked at each of them with IR microscope. We took large area IR scans of entire wafers

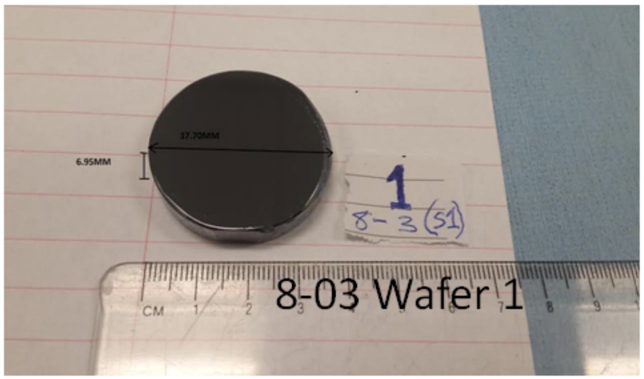
We then used Saucedo solution etching to reveal different grains on the wafers.



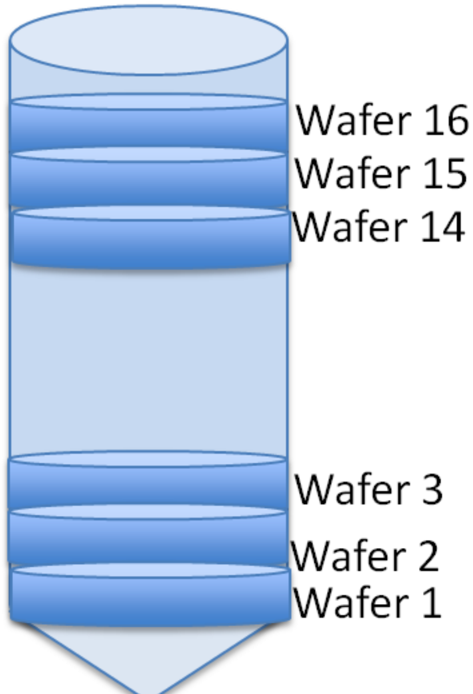
Saucedo solution etching reveals different grains on the wafers. We use the grain boundaries as guides to enable us harvest different regions of the crystals as we need. We are interested in 1) single grain regions, 2) regions with grain boundaries and twins.

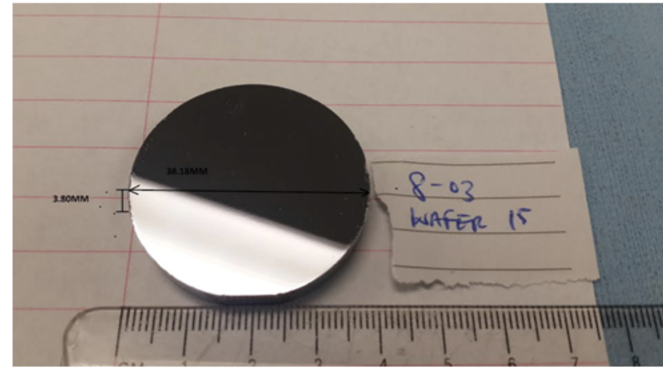
Ingot 8-03

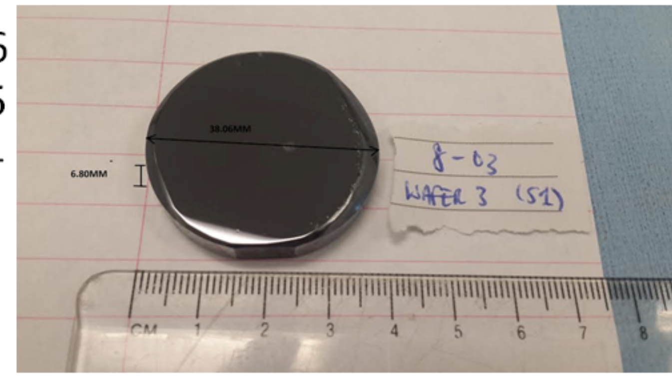

37.93 MM
6.88MM
8-03
WAFER 2
(S1)

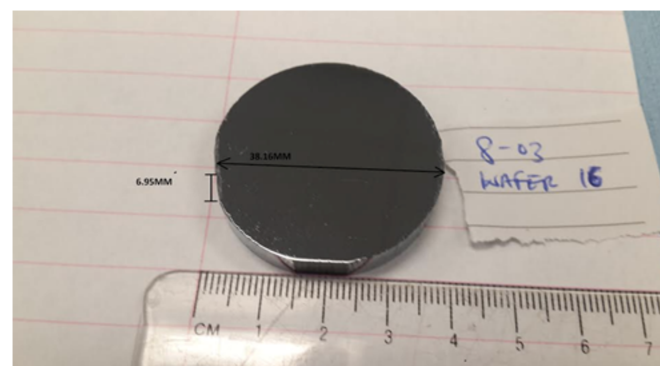

37.70MM
6.95MM
1
8-3 (S1)
8-03 Wafer 1


38.24MM
6.43MM
8-03
WAFER 14

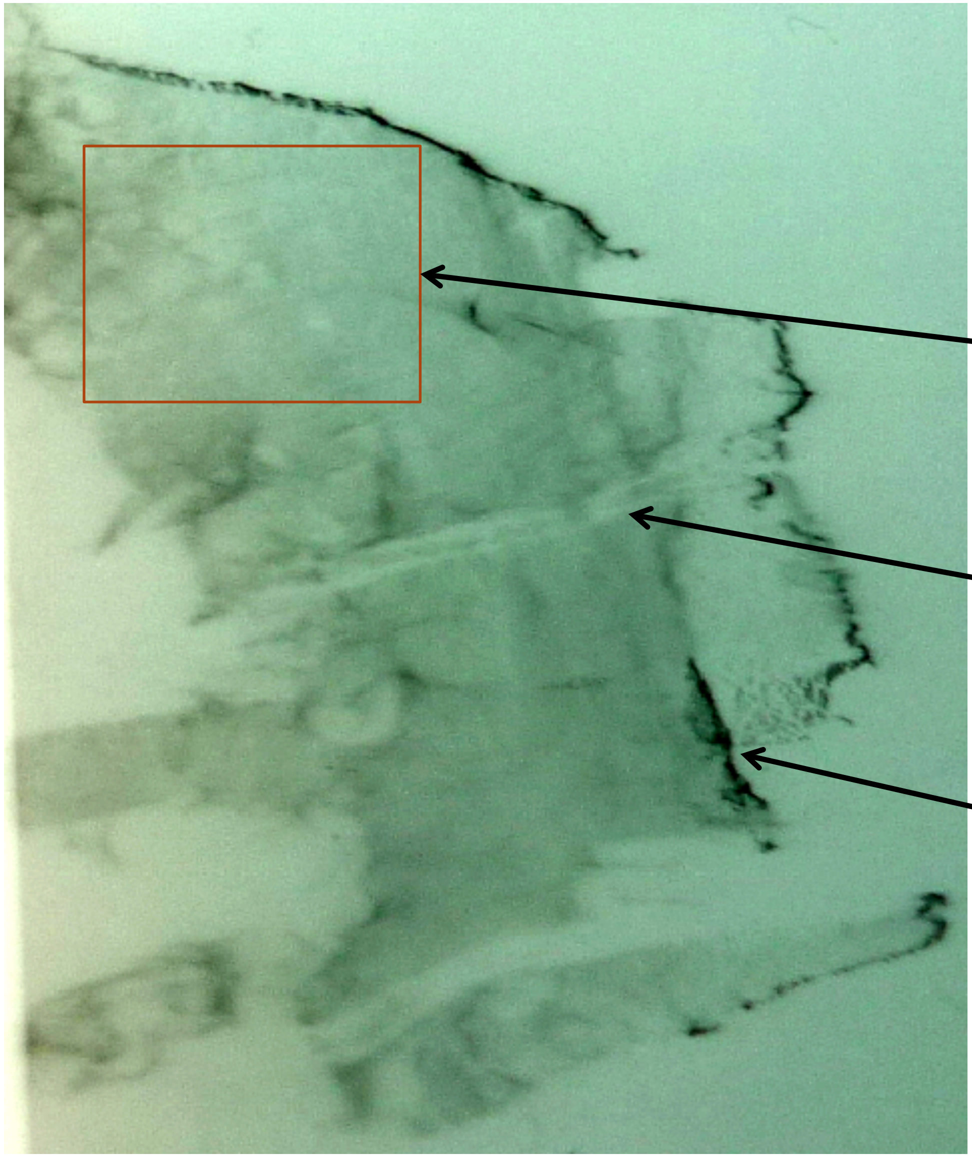

Wafer 16
Wafer 15
Wafer 14
Wafer 3
Wafer 2
Wafer 1


38.18MM
3.80MM
8-03
WAFER 15

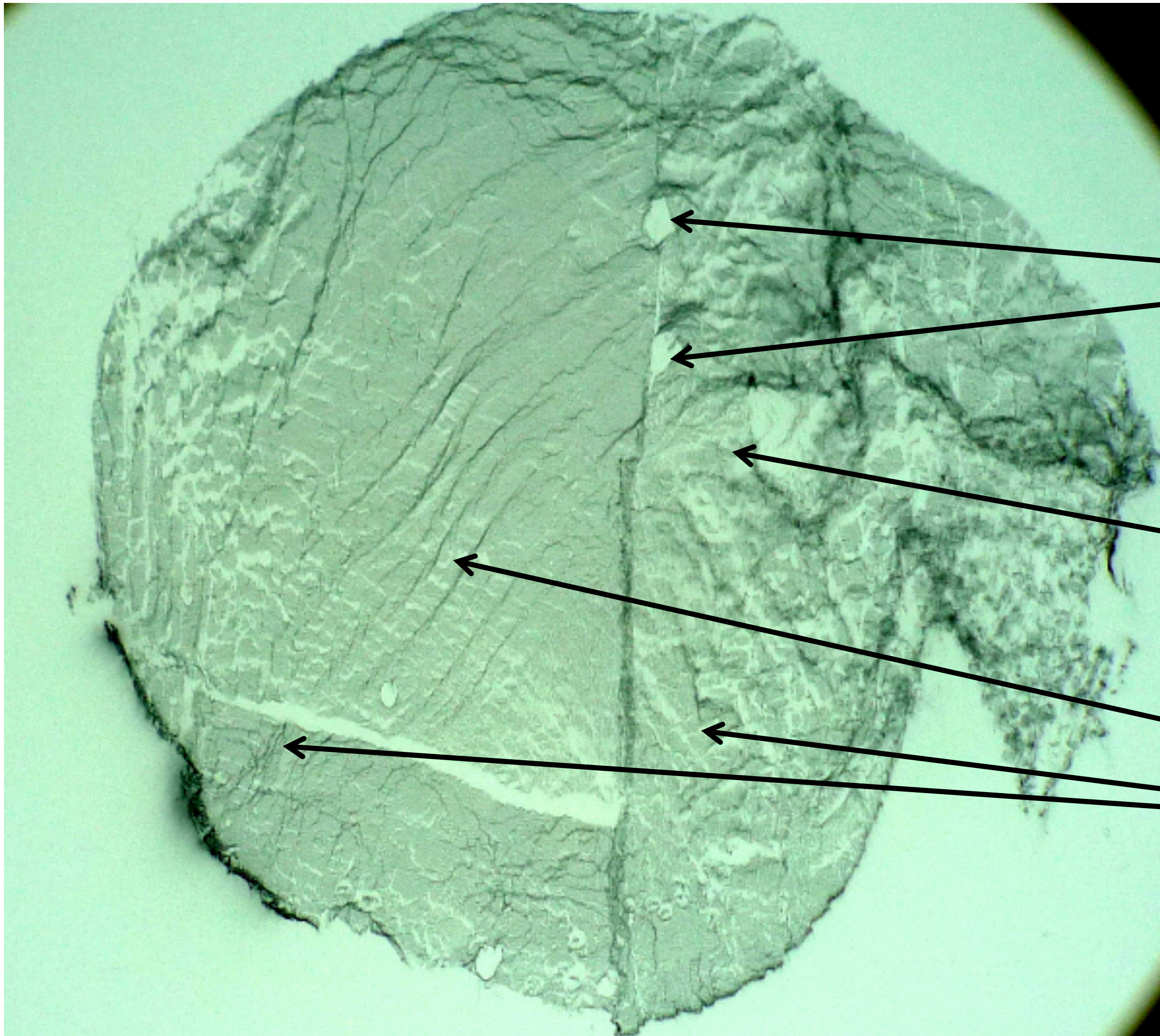

38.06MM
6.80MM
8-03
WAFER 3 (S1)

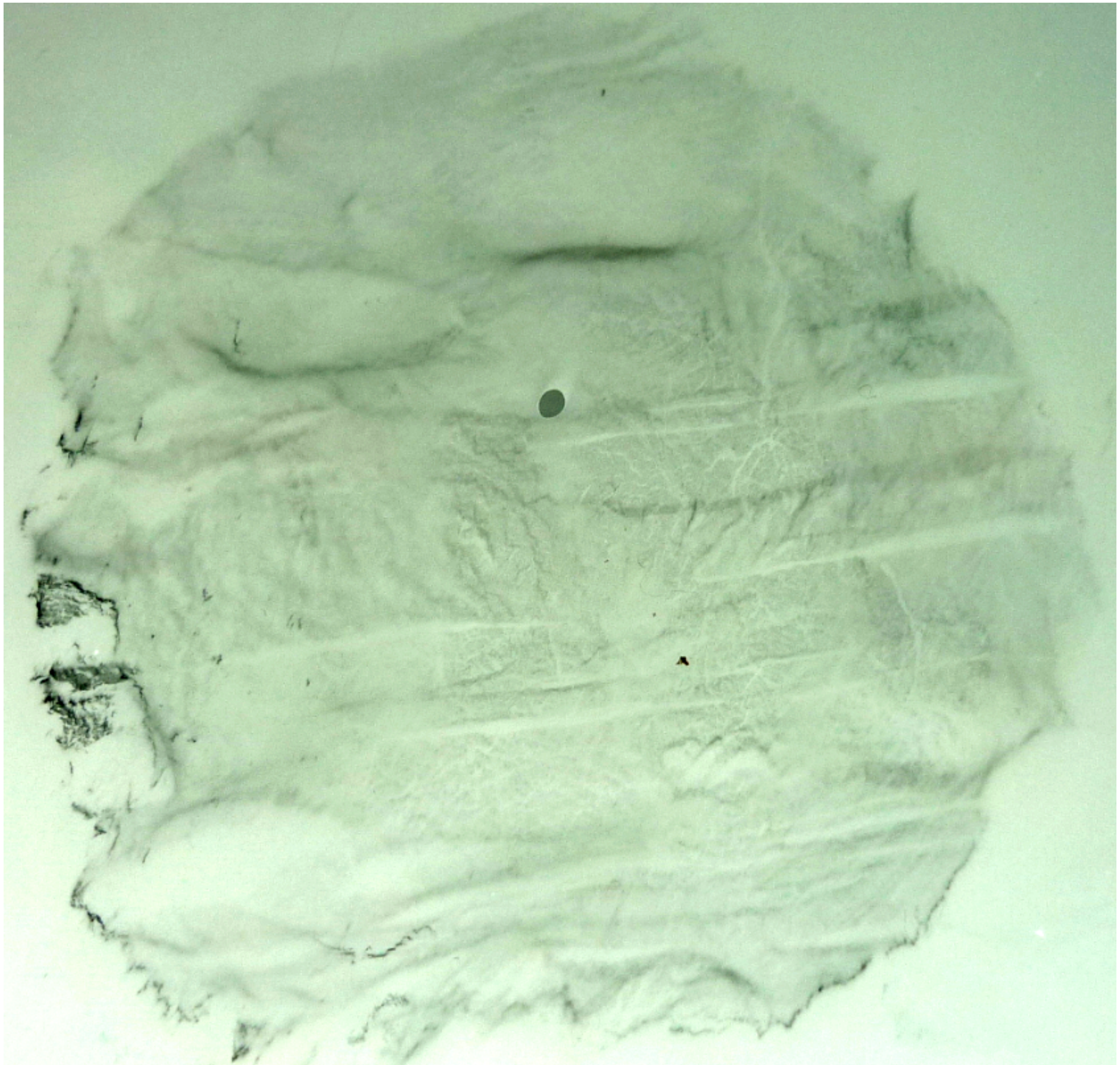

38.16MM
6.95MM
8-03
WAFER 16

Results and discussion

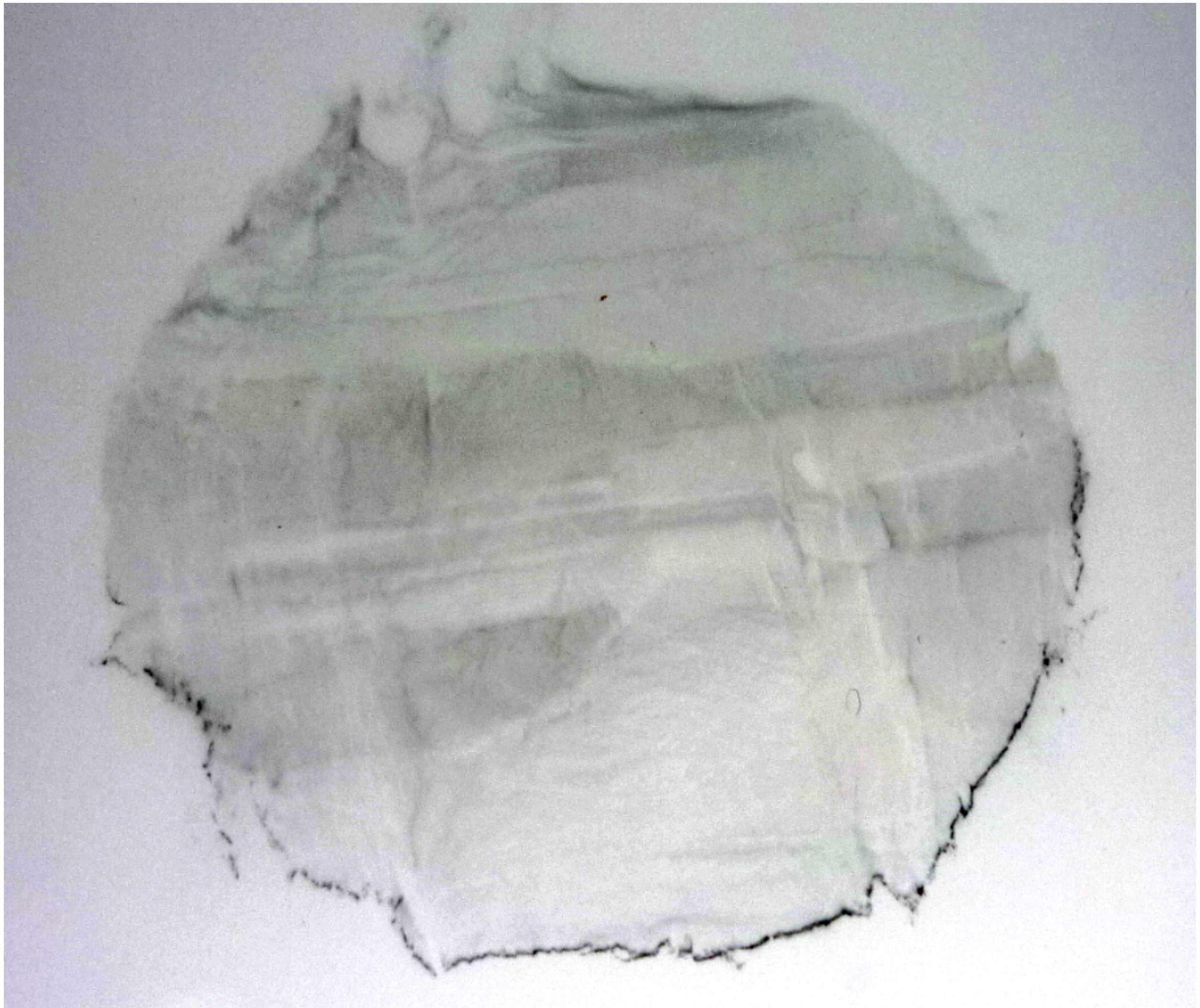


Wafer 2

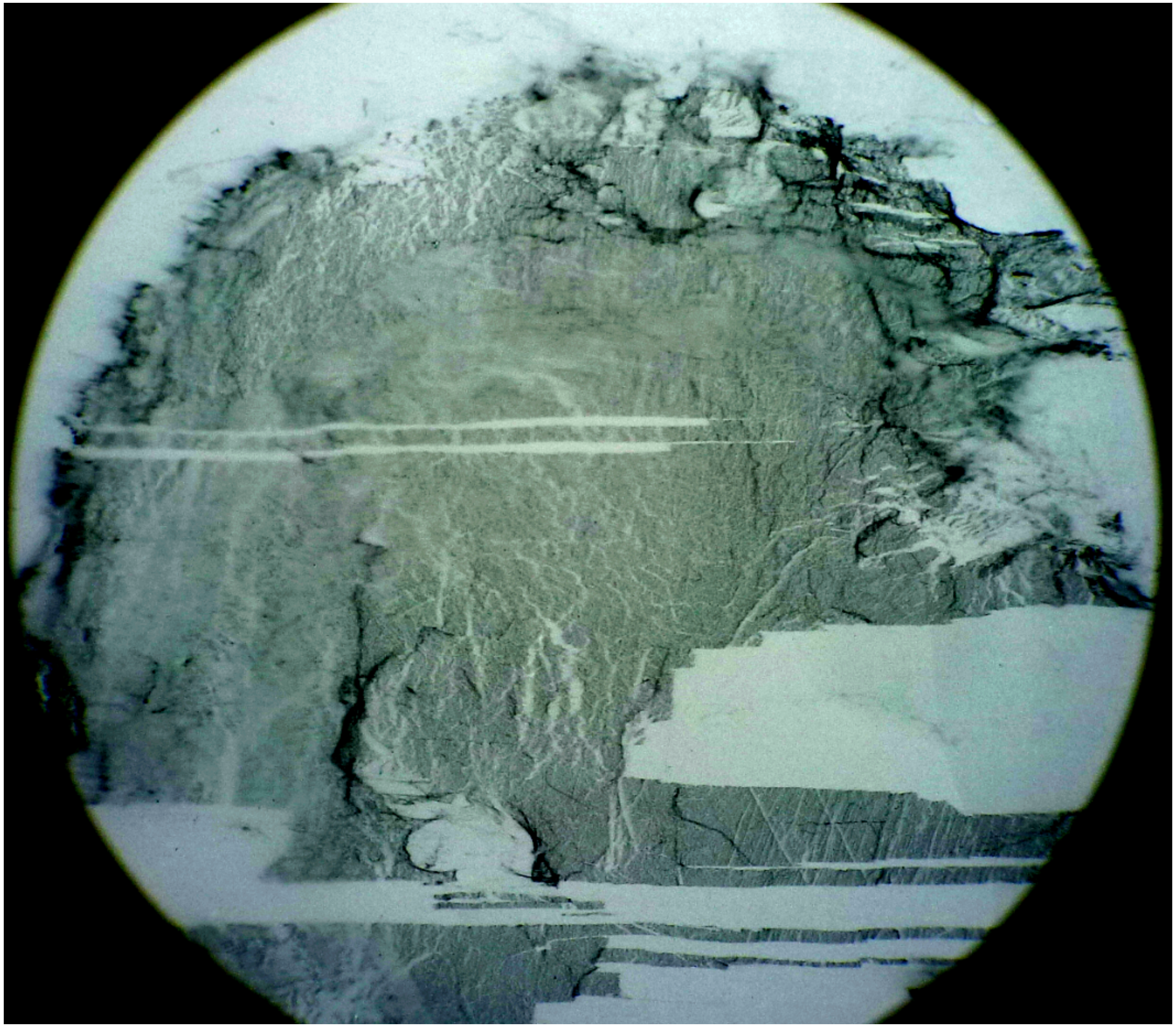




wafer 3



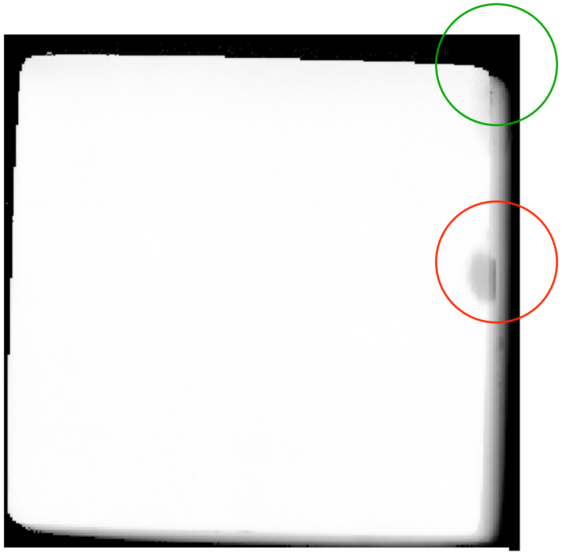
wafer 4

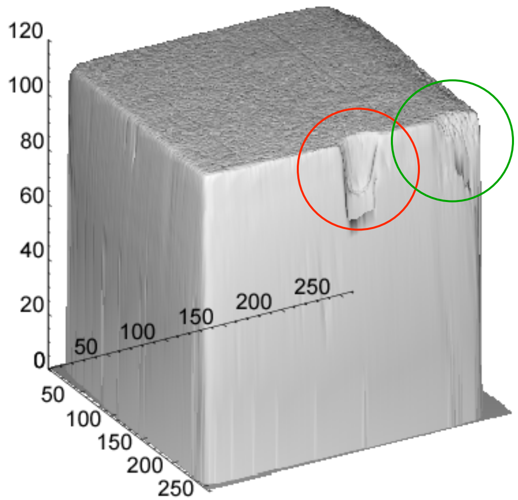


wafer 17

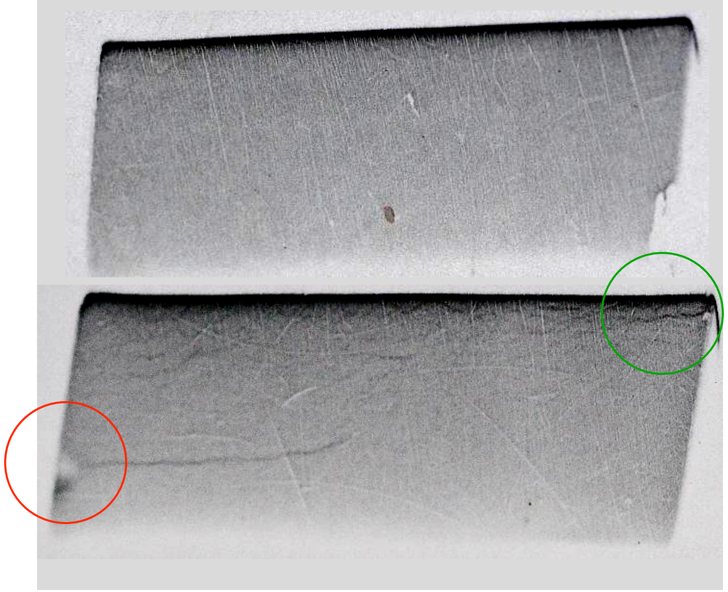
Correlation between XRDT and detector response

X-ray response map (e⁻ collection)





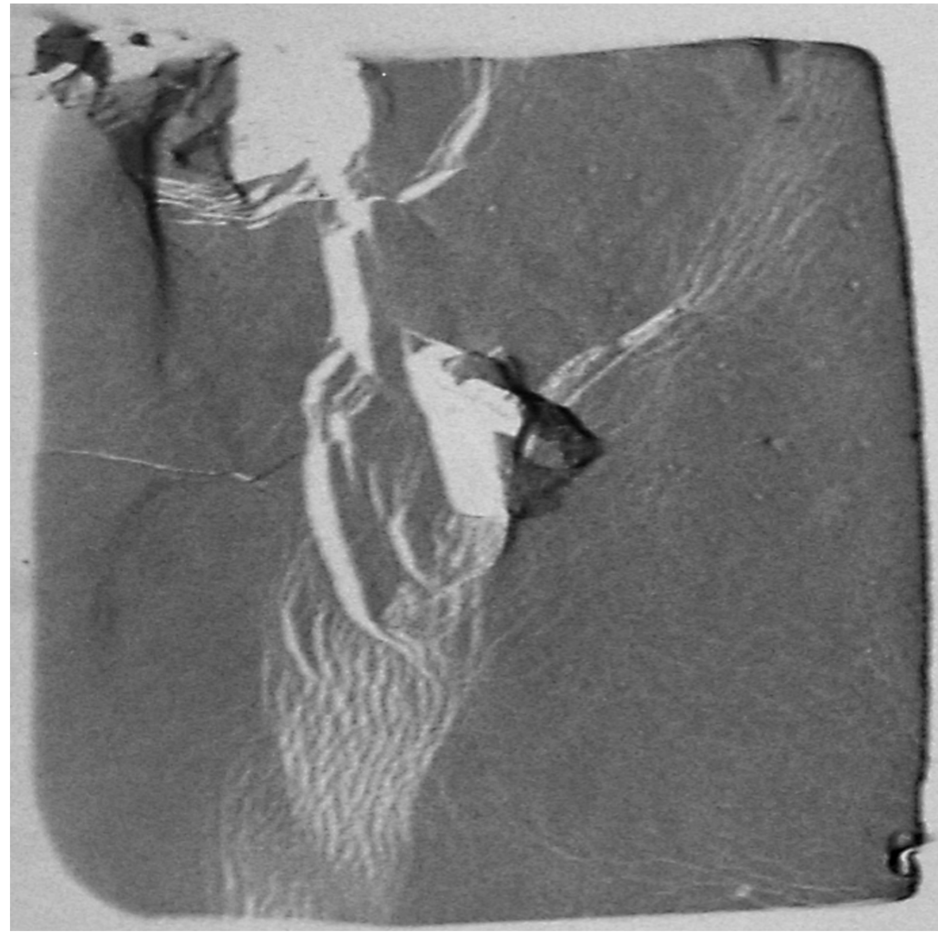
X-ray diffraction topography



Low density of dislocations observed

X-ray Response Map of Hole Collection and White-Beam X-ray Diffraction Topography Images

Hole collection X-ray map



White-Beam X-ray Togography Image

Conclusion

- WXDT enables us to observe sub-grain boundaries, that are otherwise difficult to detect with other characterization techniques.
- Technique is fast and suitable for qualitative screening of large bulk CZT crystals.
- WXDT helps to investigate the relationship between the growth conditions and dislocation formation. Large scale evaluation.
- This could increase yield of CZT crystals, especially for large scale production.

Development of Radiation Detector Simulation Environment Using Monte Carlo N-Particle Transport (MCNP)

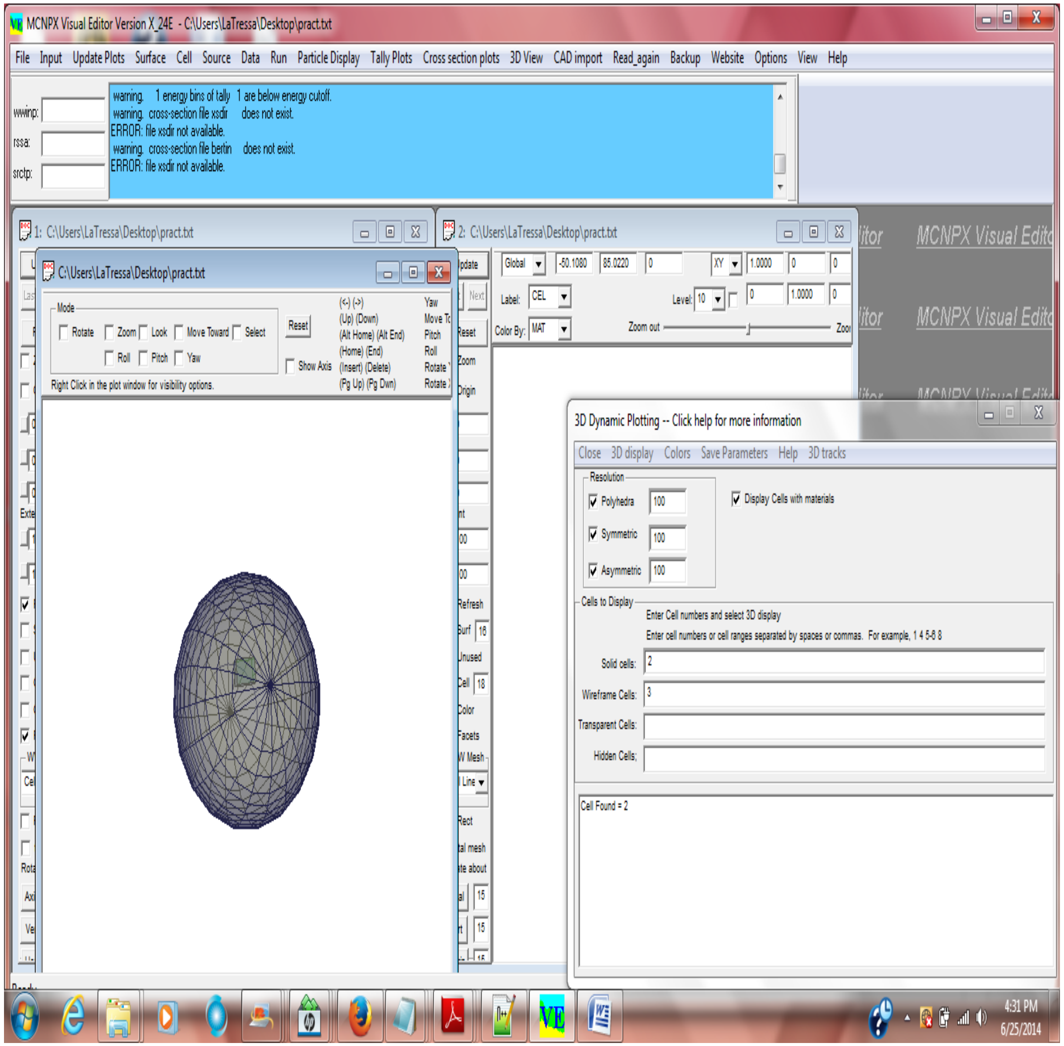
- MCNP is a software developed for the numerical simulation of neutron, photon, and electron transport throughout materials.
- MCNP was developed and is owned by Los Alamos National Laboratory (LANL) located in Northern New Mexico.
- The Alabama A&M Materials Research Lab is currently using MCNP to:

-Analyze data from simulated transport and interaction of photons, and electrons in different materials.

-To use experimental results to train the simulation environment.

Los Alamos National Laboratory

Visual Editor (Vis-Ed)



- We used Vis-Ed to plot the geometry from the input files.
- Allows us to see images that we create in 3D.
- Can also be used to plot tallies.

Sample of a 3d Image generated through MCNP Vis-Ed.

Input to Output

- Create an input file with the appropriate geometries.
- Run input file in Vis-Ed to verify the geometries.
- Run input file in MCNP6.
- Process the output files and plotted them to the their respective cases.

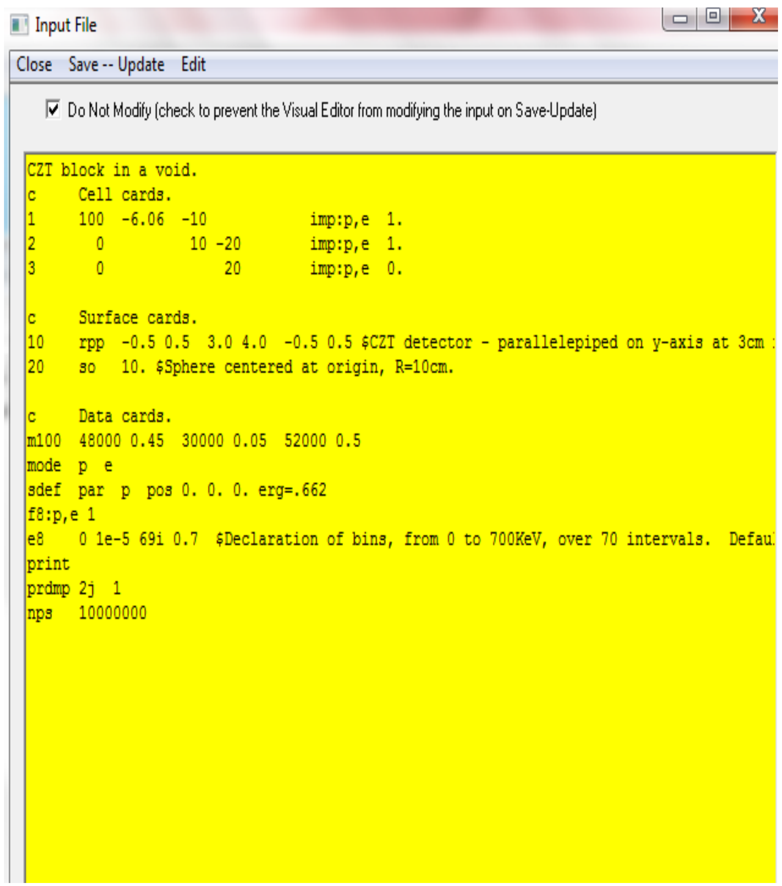
Case I

Point source Cs-137 centered at the origin of the Cartesian plane.

CZT Block 1 cm^3

Detector 3 cm from source.

Input File and View in Vis-Ed

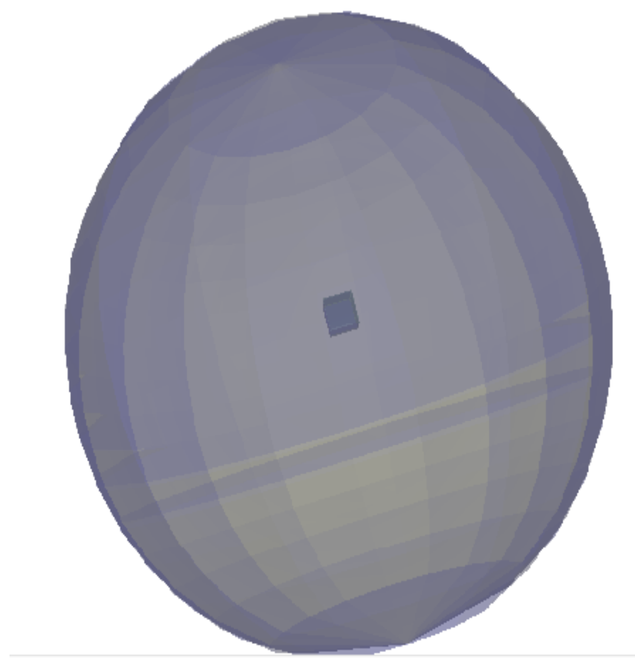


Input File

Close Save -- Update Edit

Do Not Modify (check to prevent the Visual Editor from modifying the input on Save-Update)

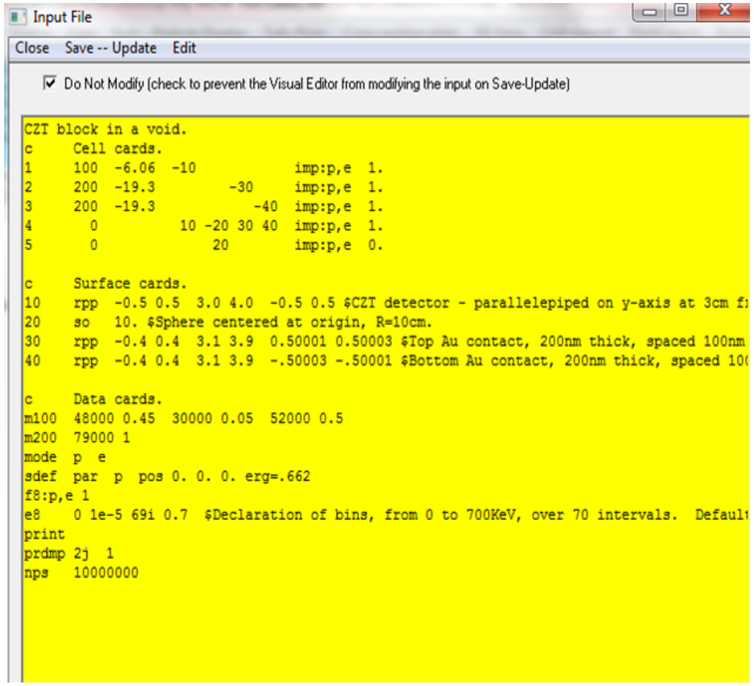
```
CZT block in a void.
c     Cell cards.
1     100  -6.06  -10           imp:p,e  1.
2       0          10 -20       imp:p,e  1.
3       0              20       imp:p,e  0.

c     Surface cards.
10    rpp  -0.5 0.5  3.0 4.0  -0.5 0.5 $CZT detector - parallelepiped on y-axis at 3cm
20    so   10. $Sphere centered at origin, R=10cm.

c     Data cards.
m100  48000 0.45  30000 0.05  52000 0.5
mode  p  e
sdef  par  p  pos 0. 0. 0. erg=.662
f8:p,e 1
e8    0 1e-5 69i 0.7  $Declaration of bins, from 0 to 700KeV, over 70 intervals.  Defau
print
prdmp 2j  1
nps   10000000
```



Case II

Point source (Cs-137) at origin.
Added gold (Au) contacts to the top and bottom of the CZT block.
Distance from source still 3 cm.

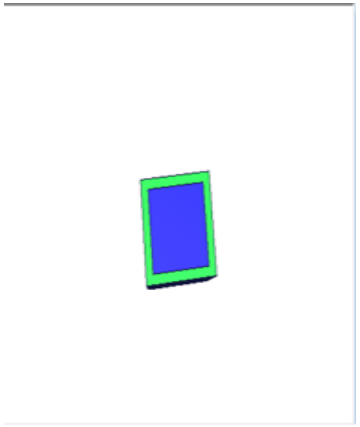
Input file and View in Vis-Ed


Input File

Close Save -- Update Edit

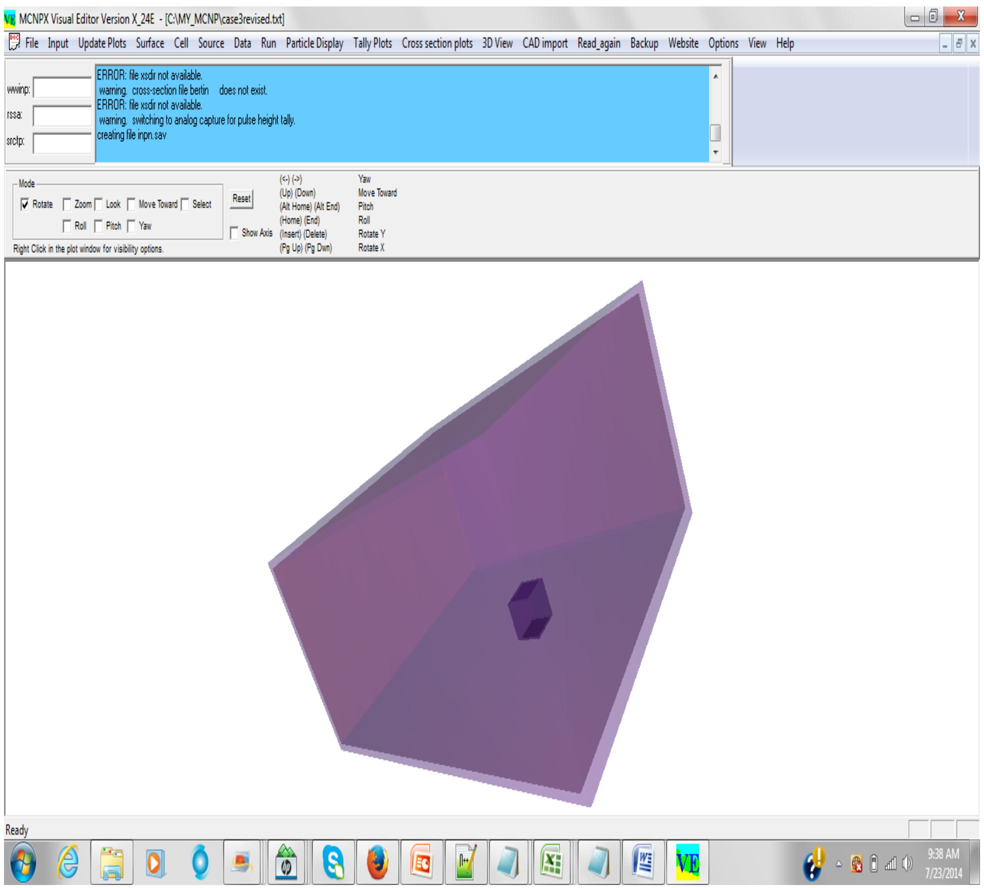
Do Not Modify (check to prevent the Visual Editor from modifying the input on Save-Update)

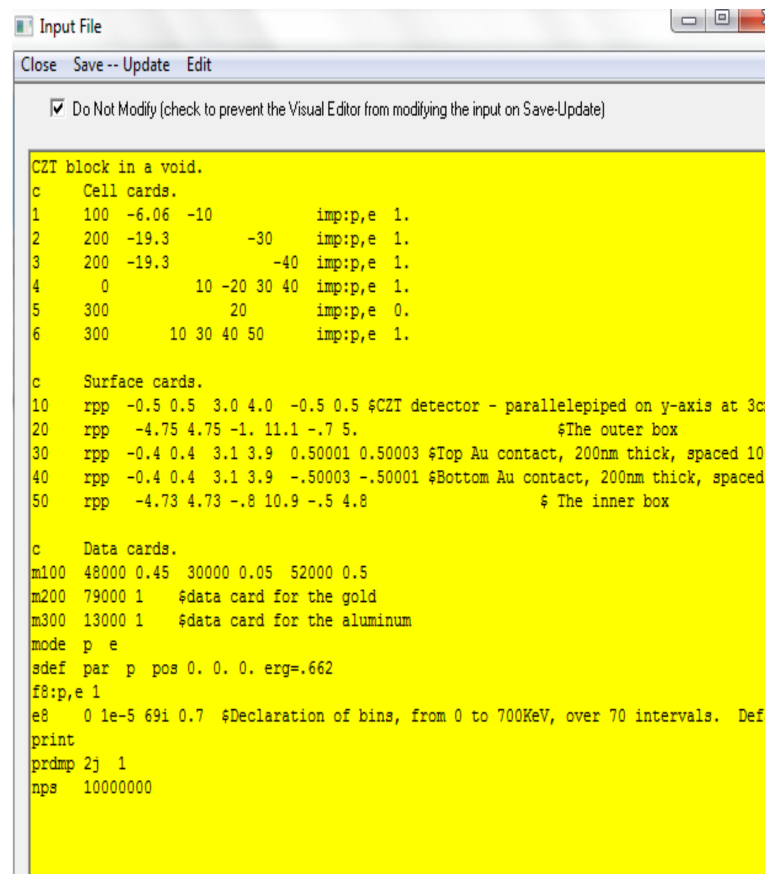
```
CZT block in a void.
c     Cell cards.
1     100  -6.06  -10             imp:p,e  1.
2     200  -19.3         -30      imp:p,e  1.
3     200  -19.3             -40  imp:p,e  1.
4       0          10 -20 30 40   imp:p,e  1.
5       0               20        imp:p,e  0.

c     Surface cards.
10    rpp  -0.5 0.5  3.0 4.0  -0.5 0.5 $CZT detector - parallelepiped on y-axis at 3cm fr
20    so   10. $Sphere centered at origin, R=10cm.
30    rpp  -0.4 0.4  3.1 3.9  0.50001 0.50003 $Top Au contact, 200nm thick, spaced 100nm
40    rpp  -0.4 0.4  3.1 3.9  -.50003 -.50001 $Bottom Au contact, 200nm thick, spaced 10(

c     Data cards.
m100  48000 0.45  30000 0.05  52000 0.5
m200  79000 1
mode  p  e
sdef  par  p  pos 0. 0. 0. erg=.662
f8:p,e 1
e8    0 1e-5 69i 0.7  $Declaration of bins, from 0 to 700KeV, over 70 intervals.  Default
print
prdmp 2j  1
nps   10000000
```



Case III

The source and detector were in a spherical void before.
The aluminum box from the experimental set up has been added to the input file.
The other parameters are the same from Case 2.



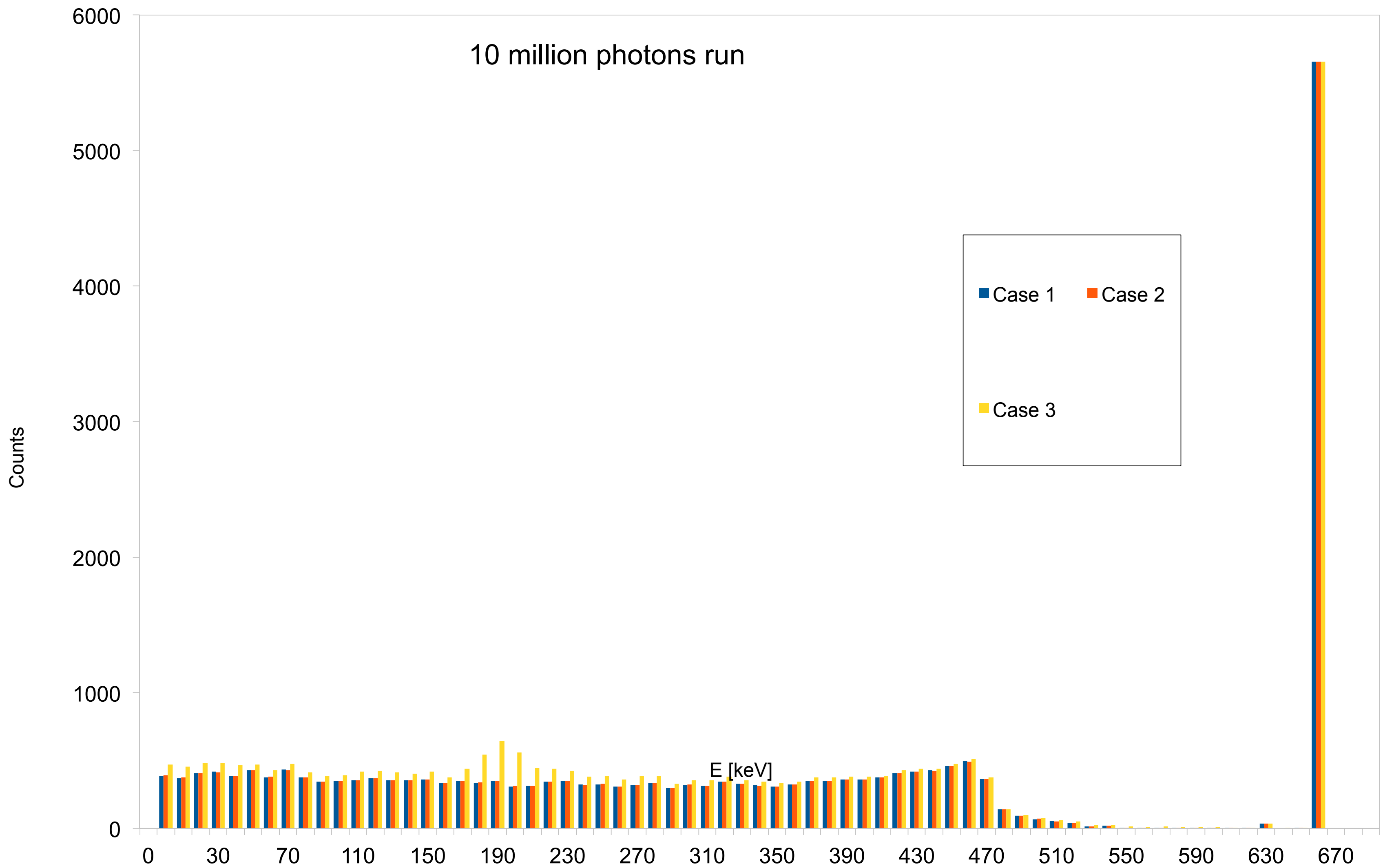

Input File

Close Save -- Update Edit

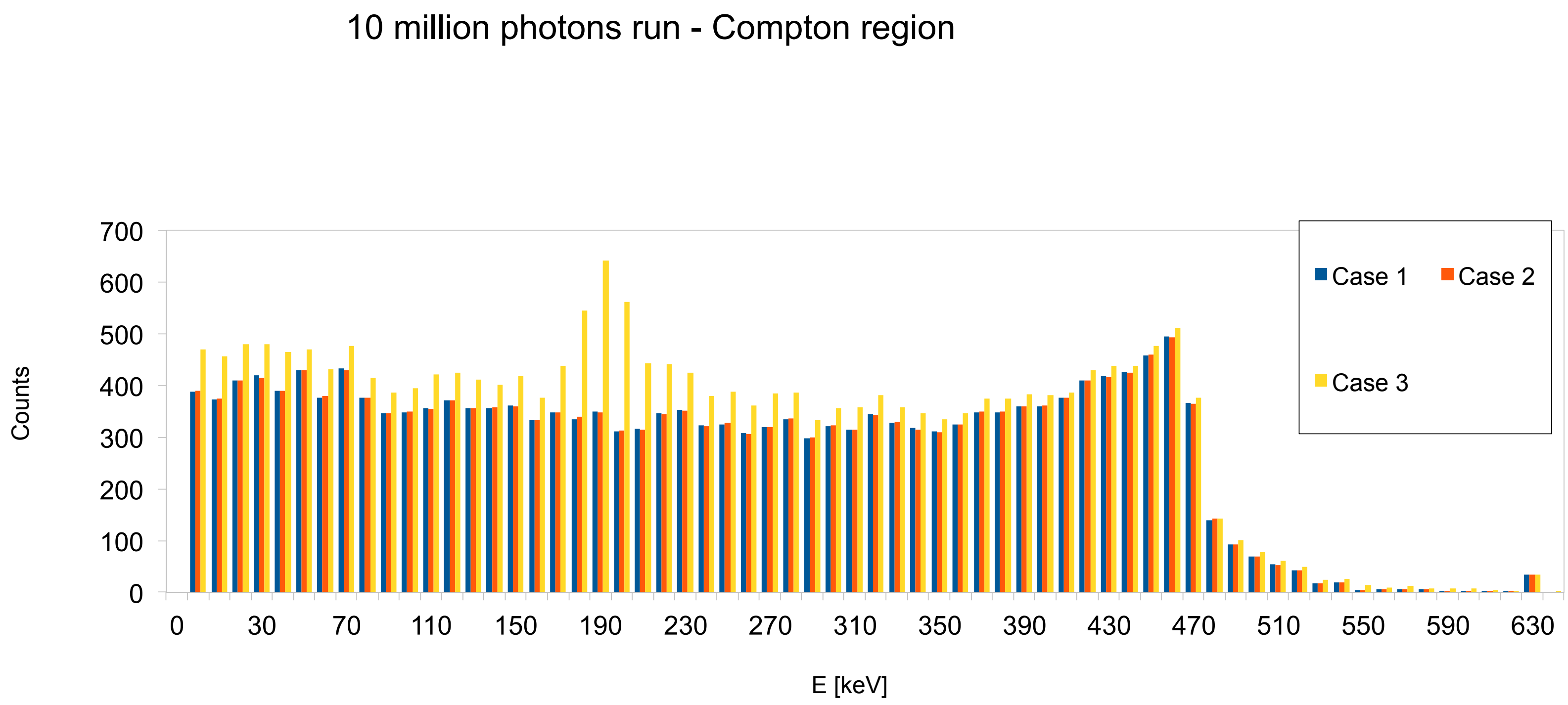
Do Not Modify (check to prevent the Visual Editor from modifying the input on Save-Update)

```
CZT block in a void.
c     Cell cards.
1     100  -6.06  -10           imp:p,e  1.
2     200  -19.3        -30     imp:p,e  1.
3     200  -19.3           -40  imp:p,e  1.
4       0         10 -20 30 40  imp:p,e  1.
5     300              20       imp:p,e  0.
6     300       10 30 40 50     imp:p,e  1.

c     Surface cards.
10    rpp  -0.5 0.5  3.0 4.0  -0.5 0.5 $CZT detector - parallelepiped on y-axis at 3cm
20    rpp   -4.75 4.75 -1. 11.1 -.7 5.                $The outer box
30    rpp  -0.4 0.4  3.1 3.9  0.50001 0.50003 $Top Au contact, 200nm thick, spaced 100n
40    rpp  -0.4 0.4  3.1 3.9  -.50003 -.50001 $Bottom Au contact, 200nm thick, spaced 1
50    rpp   -4.73 4.73 -.8 10.9 -.5 4.8             $ The inner box

c     Data cards.
m100  48000 0.45  30000 0.05  52000 0.5
m200  79000 1    $data card for the gold
m300  13000 1    $data card for the aluminum
mode  p  e
sdef  par  p  pos 0. 0. 0. erg=.662
f8:p,e 1
e8    0 1e-5 69i 0.7  $Declaration of bins, from 0 to 700KeV, over 70 intervals.  Defau
print
prdmp 2j  1
nps   10000000
```

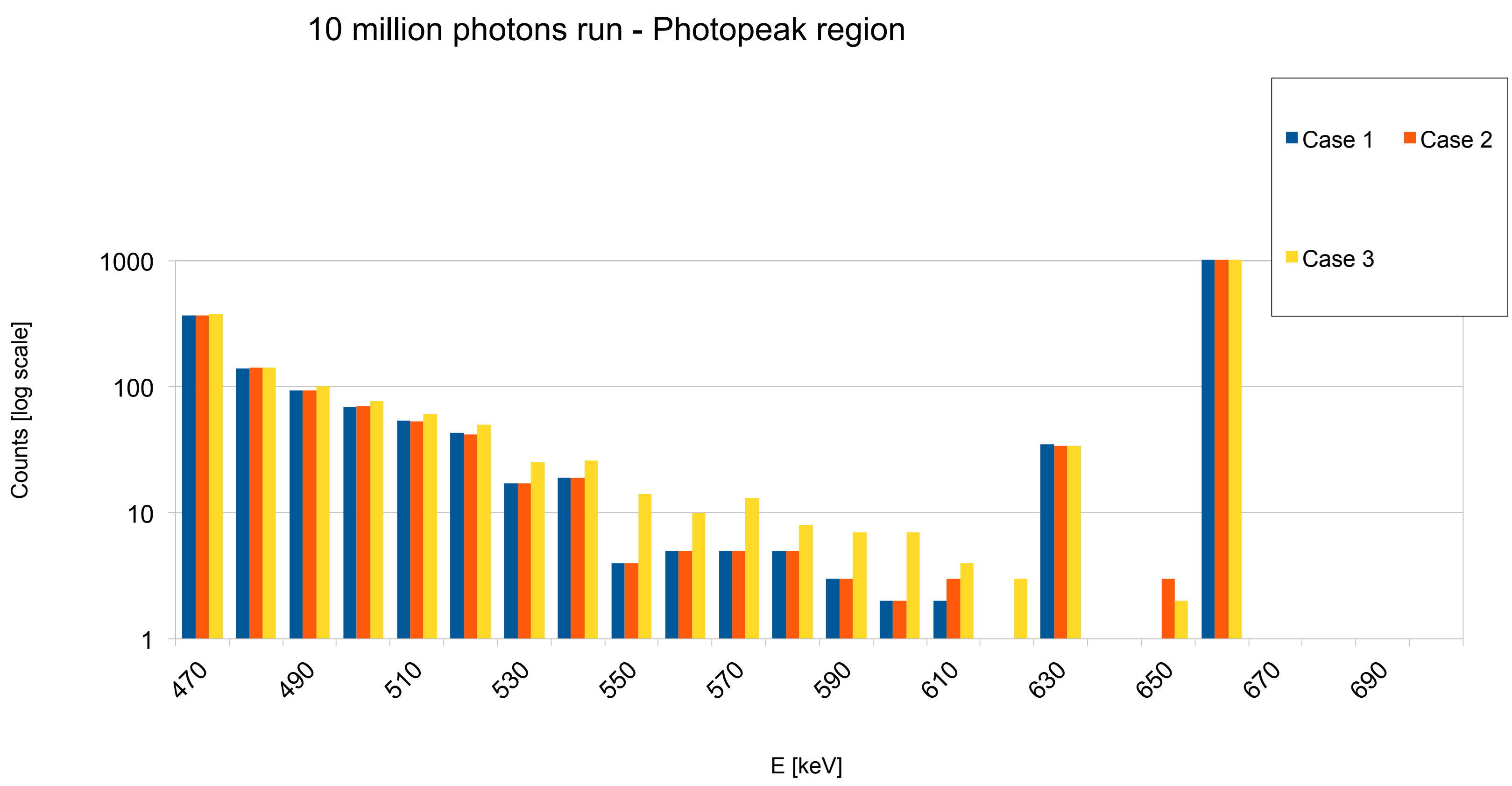
Results in Cases I-III



Compton Region



Photopeak Region



Observations

- There was no change in the photopeak count.
- No major differences between cases 1 and 2.
- Case 3 shows some major differences from the previous two, in the Compton region and the region between the Compton shoulder and photopeak.
- Case 3 shows a retro peak feature between 170 and 240 KeV, and increased count at the very low energy end.

Observations

- Addition of Au contacts does not change significantly, the outcome of the modeling/Au contacts are not a significant parameter.
- Neither addition(contacts or enclosure) affected the photopeak count; if the photopeak is the only gauge to assess the quality of detection, these parameters can be left out of the modeling process to speed up the simulation.
- **Charge transport is needed!**

Future MCNP Work

- Tellurium inclusions will be added into the CZT.
- The influence of the following parameters on energy spectrum will be explored:
  - Number of inclusions.
  - Size of inclusions.
  - Position of inclusions.
  - Shape of inclusions.

VFP 2015

Interface modification of CdZnTe-based radiation detectors by glancing angle ion sputtering

Introduce a novel crystal processing step: glancing ion sputtering
Characterize metal-semiconductor interface formed

- Joint research between BNL and AAMU
- Abstract submitted to SPIE Optics and Photonics Conference, San Diego, CA, August 9-15, 2015

Abstract: CdZnTe has been well investigated as a top choice for room temperature radiation detectors due to its attractive physical and opto-electronic properties and room-temperature operation capabilities. The bulk of CdZnTe has been extensively studied. The surface and interfacial states of the metal-semiconductor interface formed affects the performance of CdZnTe nuclear detectors and so need to be studied. In this work we have modified CZT crystal surface, and hence the metal-semiconductor interface, by adding a surface preparation step of cleansing the surfaces of the CZT crystals with argon ion at a glancing angle in high vacuum, followed by gold contact sputtering. We characterized the ion-cleansed detectors and compared their properties with un-cleansed detectors.

AAMU-CETPS

Materials Research Laboratory (MRL)

Laboratories, Instruments and Systems

Accelerators

i. Pelletron
ii. Tandetrum
iii. Ion implanter

Deposition Systems

i. IBAD - Physical Vapor Deposition (PVD)
ii. Magnetron Sputtering
iii. Chemical Vapor Deposition (CVD)
iv. Molecular Beam Epitaxy (MBE)

Sample Preparation Laboratory

i. Diamond wheel
ii. Ultrasonic cleaners
iii. Ovens and furnaces
iv. Lapping/Polishing Systems

Electrochemistry Laboratory

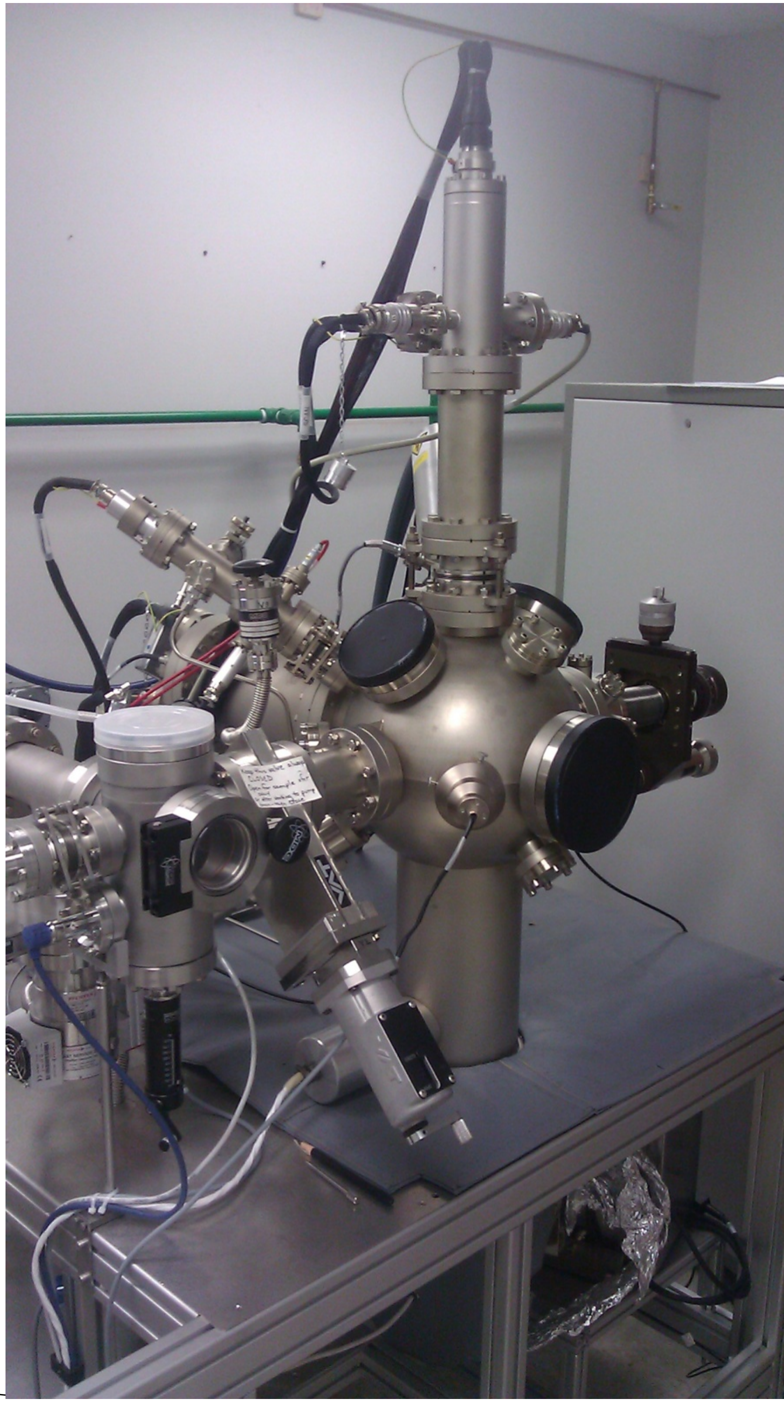
Electroplating/ Electrodeposition

Machine Shop

Other Characterization Equipment

1. Surface Characterization systems
   i. X-ray Photoelectron Spectroscopy (XPS)
   ii. Auger Electron Spectroscopy
   iii. Ultraviolet-Visible Spectroscopy
   iv. Scanning Electron Microscopy
2. Atomic Force Microscope (AFM)
3. Raman Spectroscope
4. Fourier-Transform Infrared Spectroscope (FTIR)
5. Optical Absorption Spectrometer
6. Fluorescence Spectrometer
7. Seebeck Effect System
8. Van-Der Pauw / Hall Effect System
9. Cyclic Voltammeter

Fully Functional Surface Analysis Lab



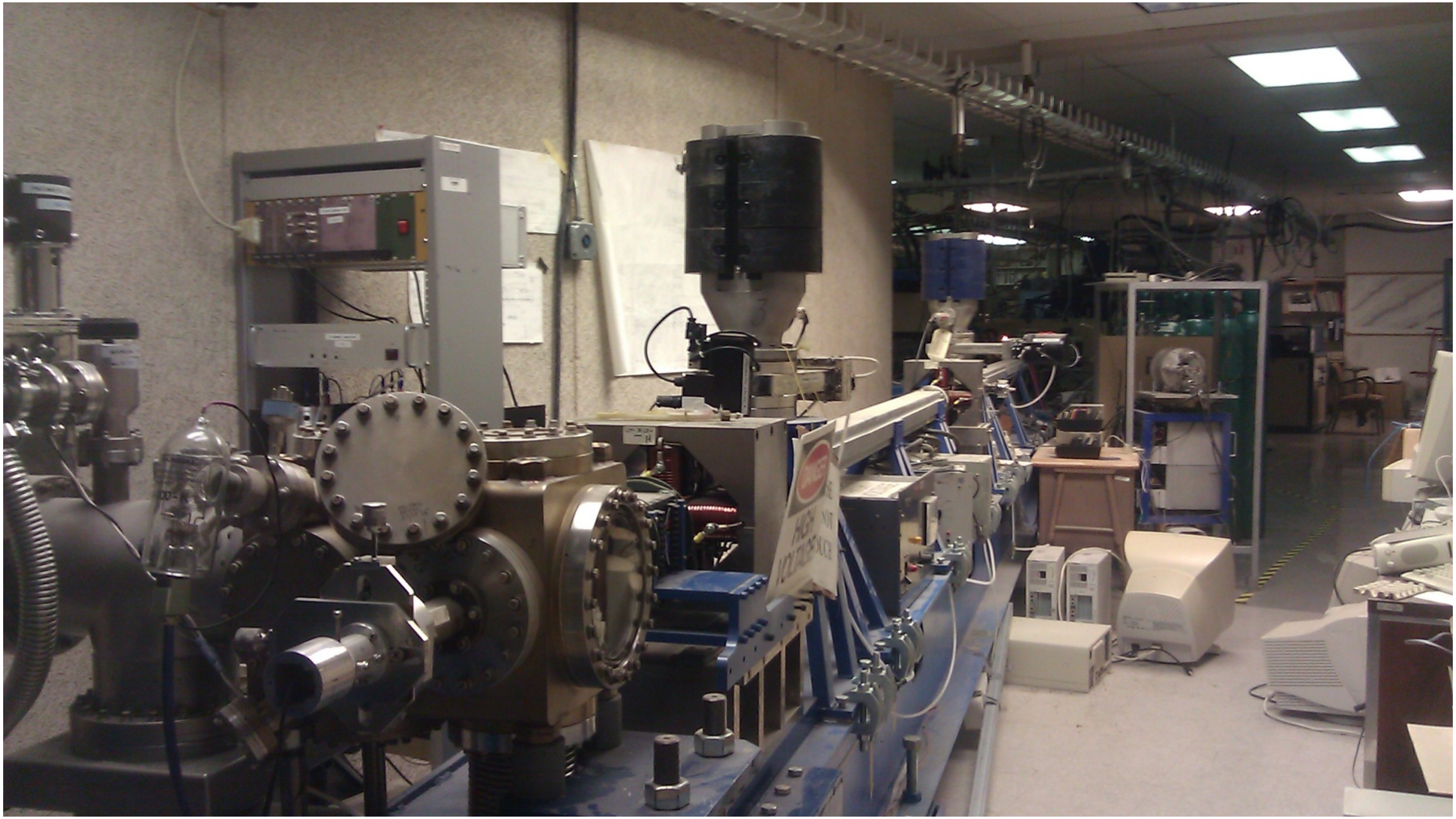
Set-up for surface analyses:

SEM
XPS
AES

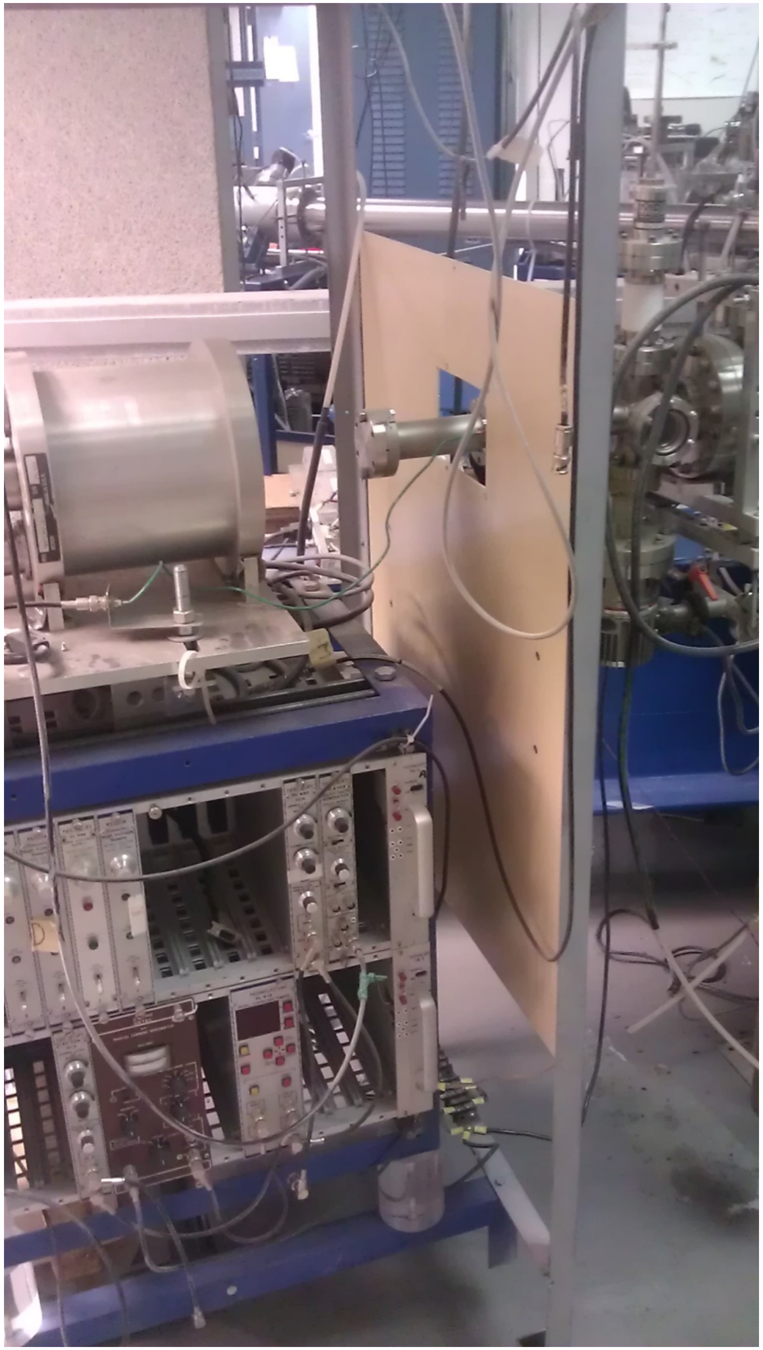
Low Energy ion implanter (5 – 200 keV)

2.1 MV tandem particle accelerator, RF and sputtering ion sources

Beam lines from accelerator

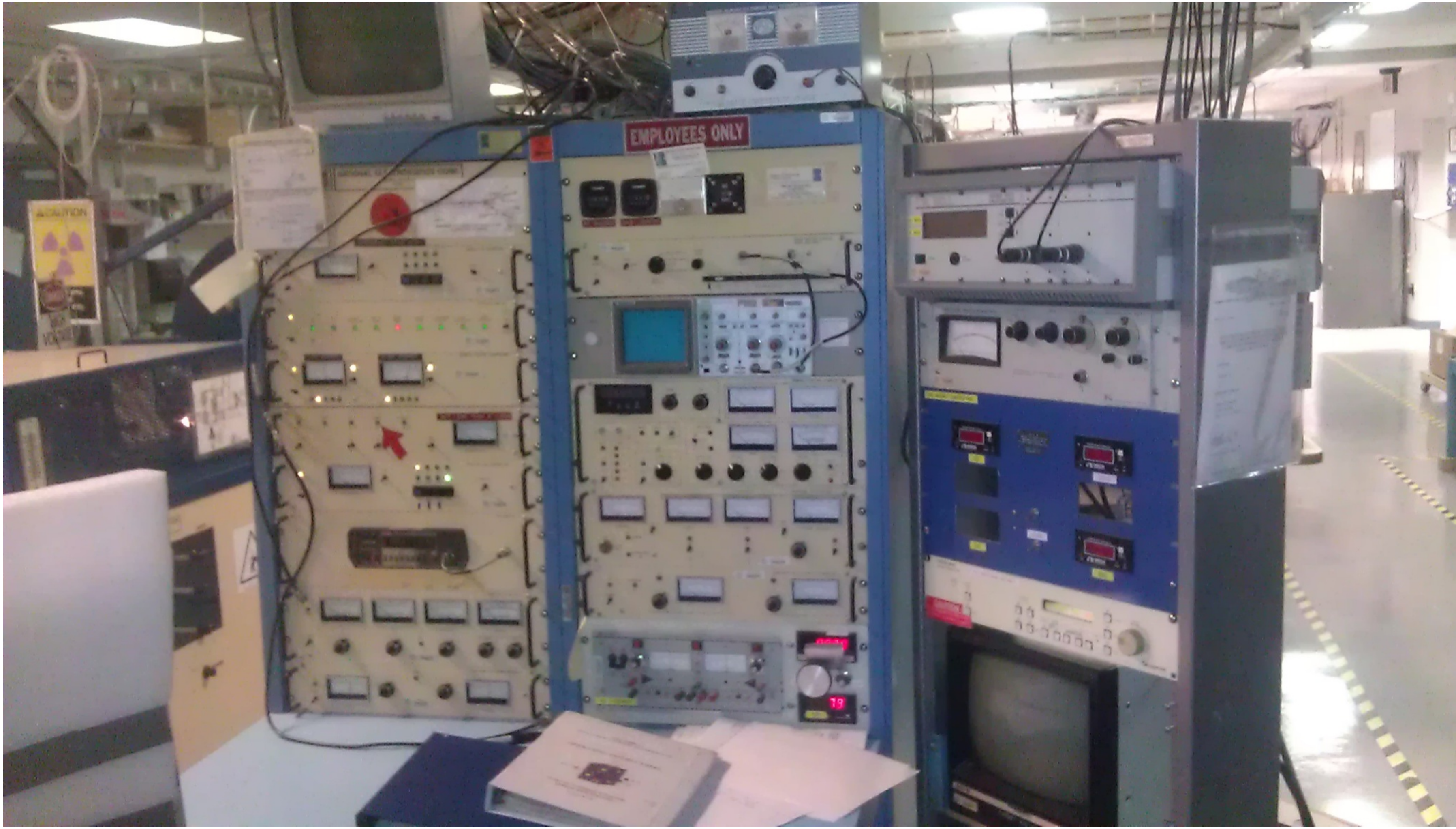


Microbeam line



Nuclear Reaction Analysys Station for Hydrogen profiling (uses ^{15}N beams)

Ion bombardment, PIXE, RBS/Channeling endstations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SIU
School of Engine
150